Recent results from Belle II

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Outline

Abbreviations

Collider

- The superKEKB collider
- The Belle II detector

Recent results from Belle II

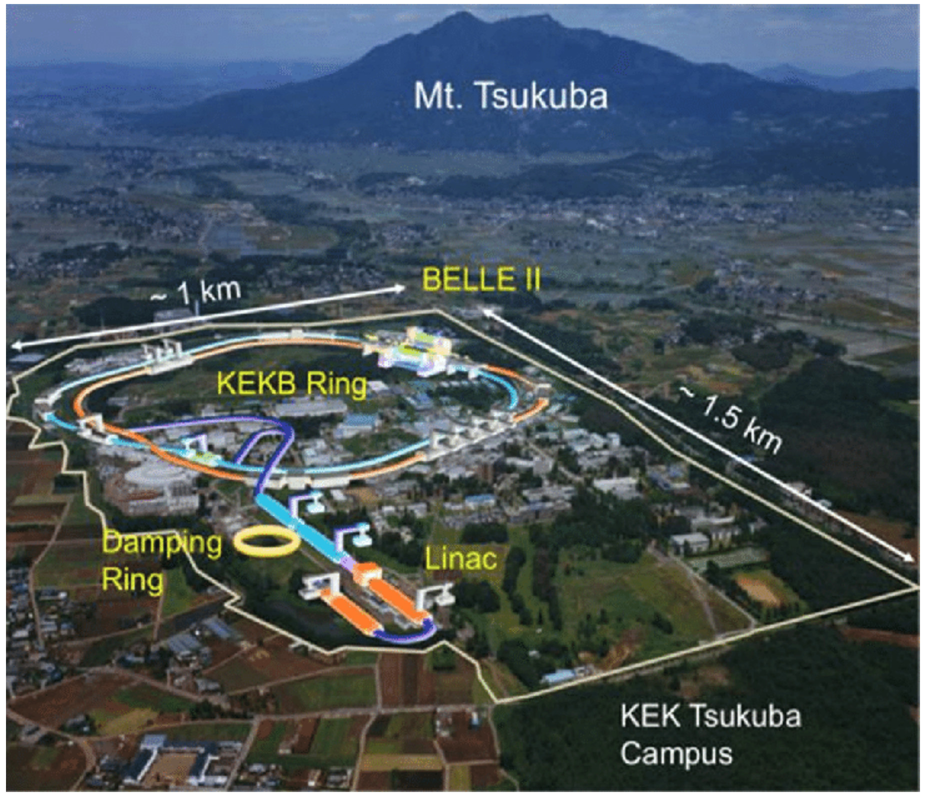
- Physics program at Belle II
- A brief introduction to some physics areas
- Followed by recent results

Summary and outlook

- Future prospects of Belle 2

- Standard Model: SM
- New Physics: NP
- Interaction point: IP
- Electroweak: EW
- Quantum Chromodynamics: QCD
- Flavor Changing Neutral Current: FCNC
- Multivariate Analysis: MVA
- Boosted Decision Tree: BDT
- Full Event Interpretation: FEI
- Kernel Density Estimation: KDE
- Boyed-Grienstein-Lebed: BGL
- Caprini-Lellouch-Neubert: CLN
- Bourrely-Caprini-Lellouch: BCL

The SuperKEKB collider (Luminosity frontier)



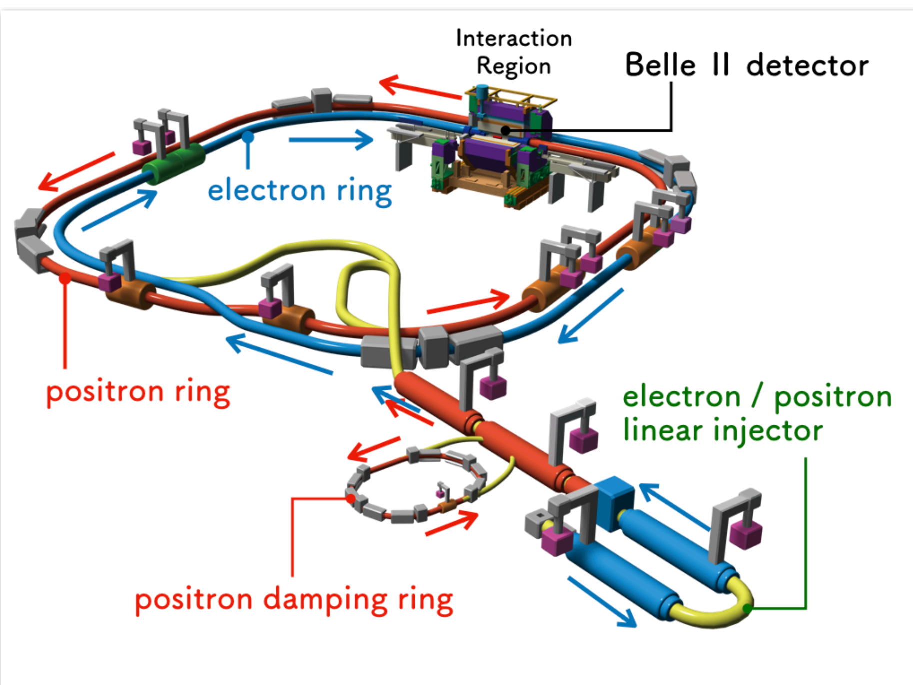
- Goal to achieve intantaneous luminosity ($\mathscr{L}$) of 6×10^{35} cm^{-2}s^{-1} and integrated $\mathscr{L}$ of 50 ab^{-1} to meet various physics requirements

Lorentz factor — Beam size at IP — Beam current — Vertical beam-beam parameter at IP

$$L = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{\pm}\xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

e^- radius — Vertical beta function at IP — Reduction factors

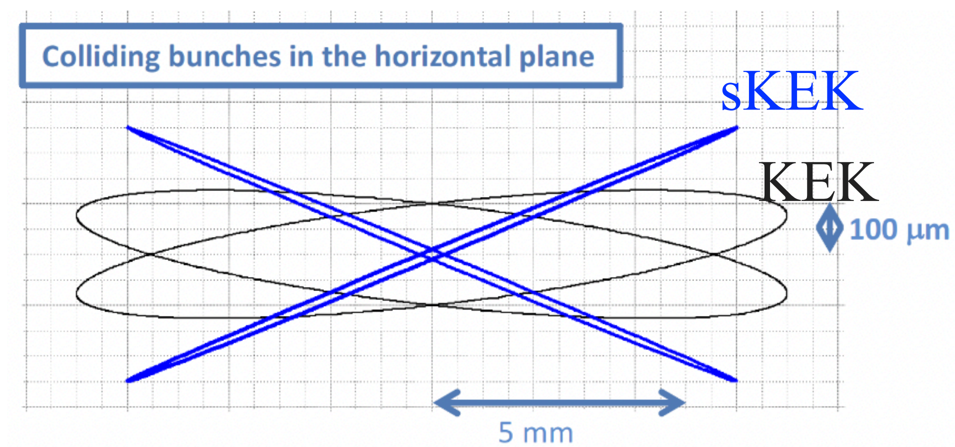
- β_y^* is a function related to the transverse beam size along the beam trajectory



In comparison to KEKB

- β_y^* is reduced by 1/20
- Beam currents are doubled ($I_{e^-} = 2.60$ A, $I_{e^+} = 3.60$ A)
- Lesser asymmetry in beam energy is to reduce backgrounds ($E_{e^-} = 4.0$ GeV, $E_{e^+} = 7.0$ GeV)
- The crossing angle is quadrupled (83 mrad)

- Nano-beam scheme (*Raimondi*)

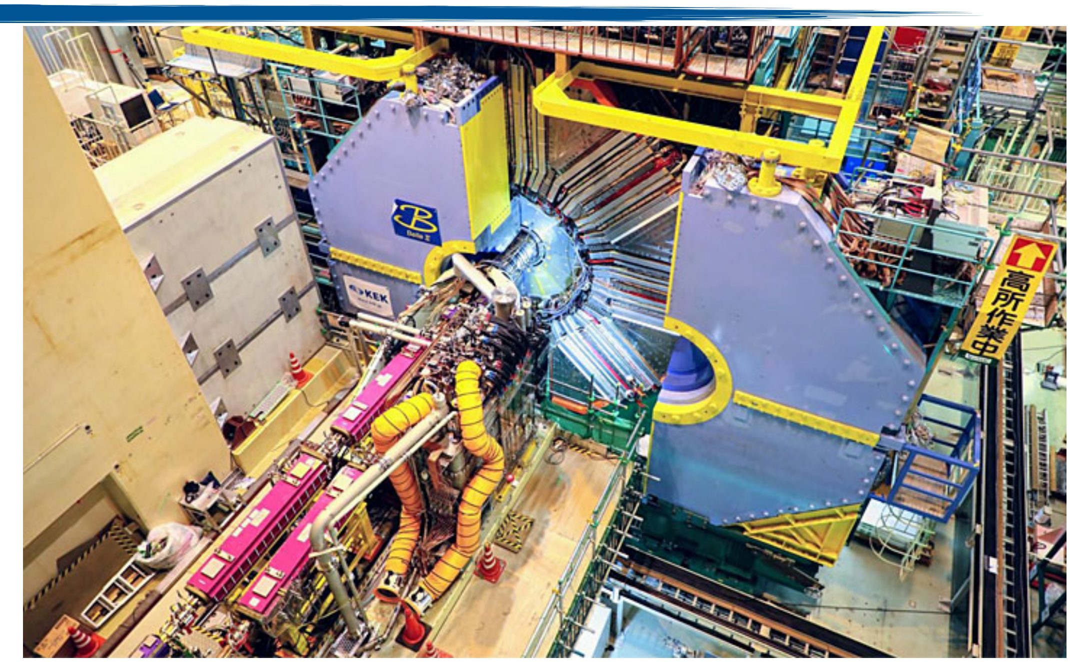


50 X more data than KEKB

The Belle II detector

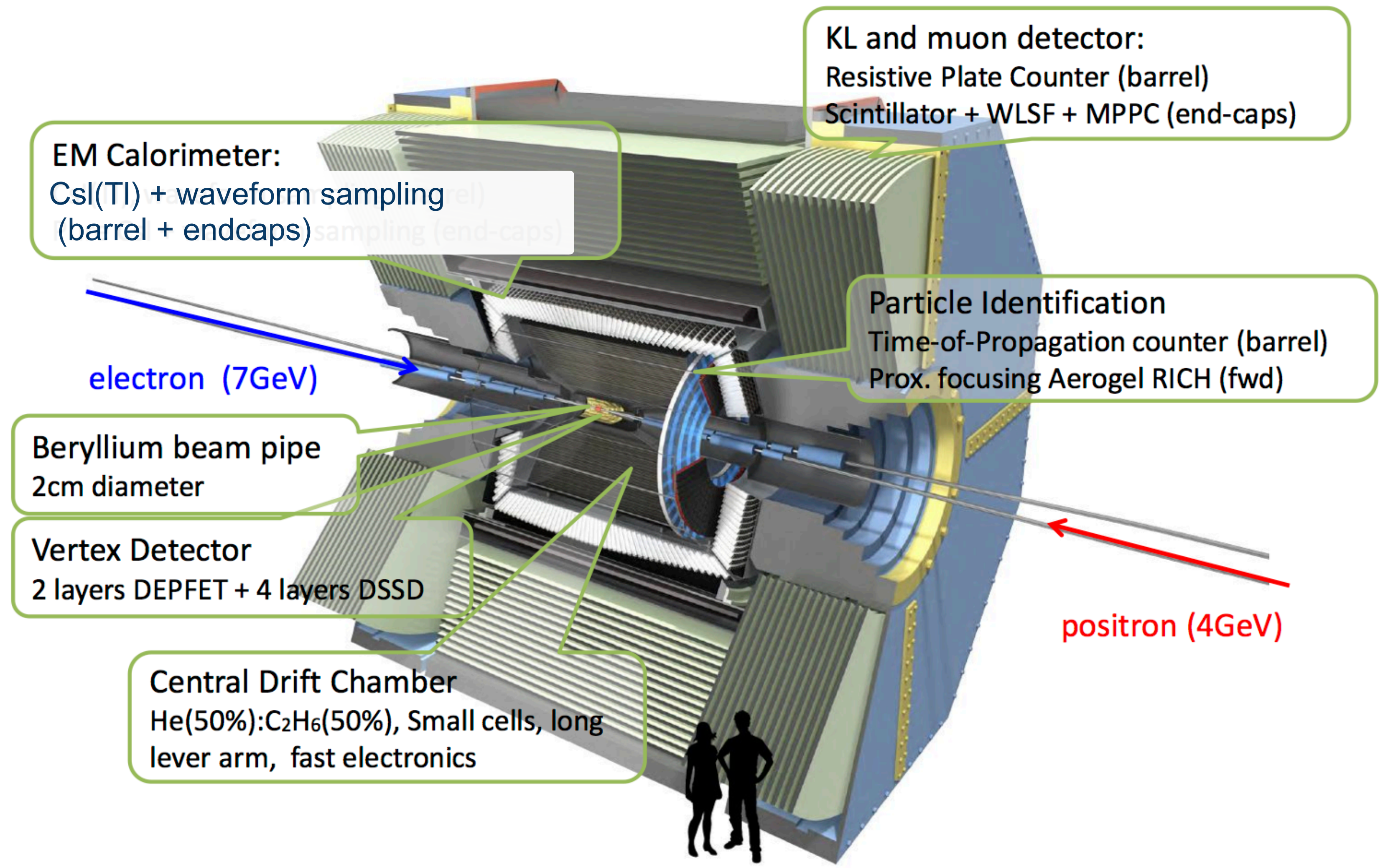
- Belle II is a general purpose next generation 4π detector
- It is designed to withstand extreme luminosity
- Currently it is undergoing upgrade (LS1) to boost data-taking capability

Belle II TDR (arXiv:1011.0352)



Improvements over Belle

- Addition of PXD to VXD with close proximity to IP improves vertex reconstruction
- Larger CDC with more sense wires
- Improvement in PID using Cherenkov imaging technique (TOP)
- Electronics improvement in the ECL
- Addition of inner layers to KLM



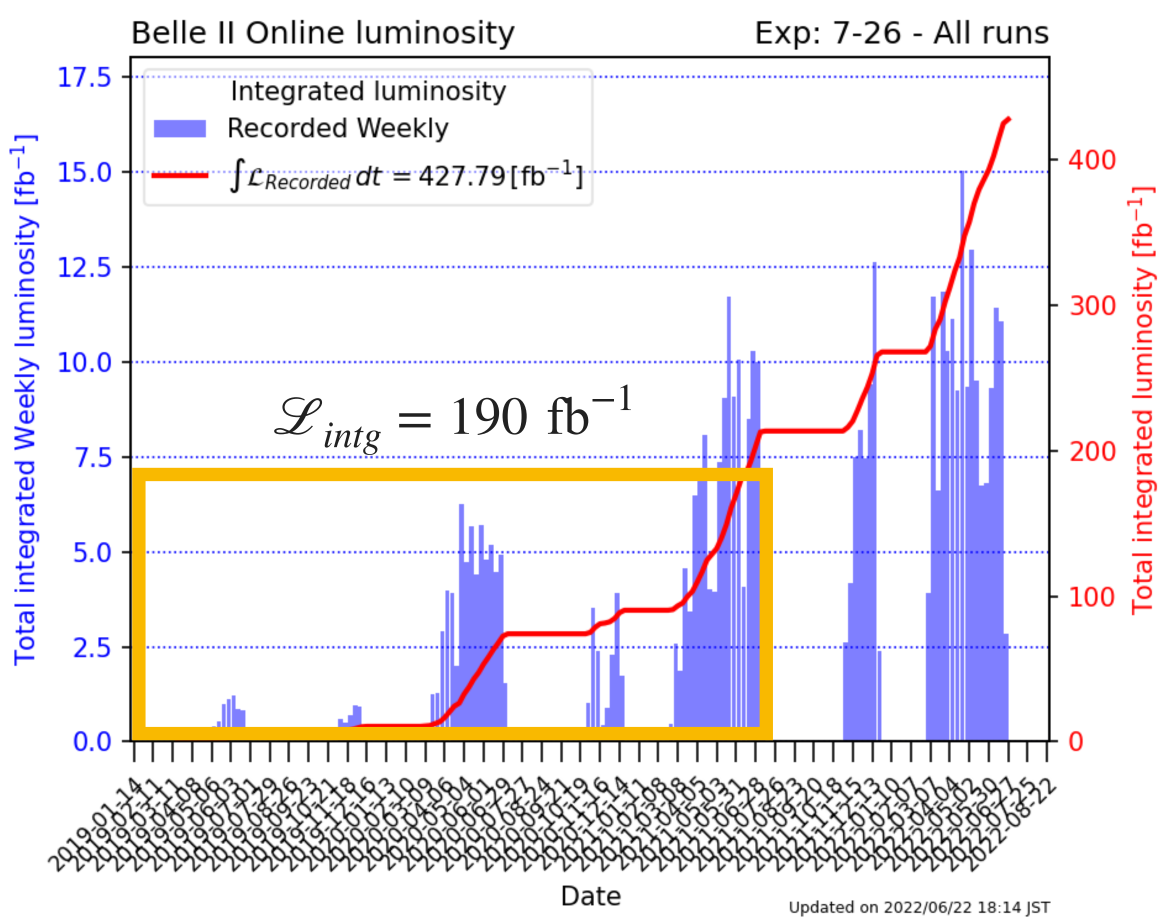
Other improvements

- New triggers introduced for dark matter searches
- Use of advanced analysis tools and techniques
- Optimal use of machine learning techniques

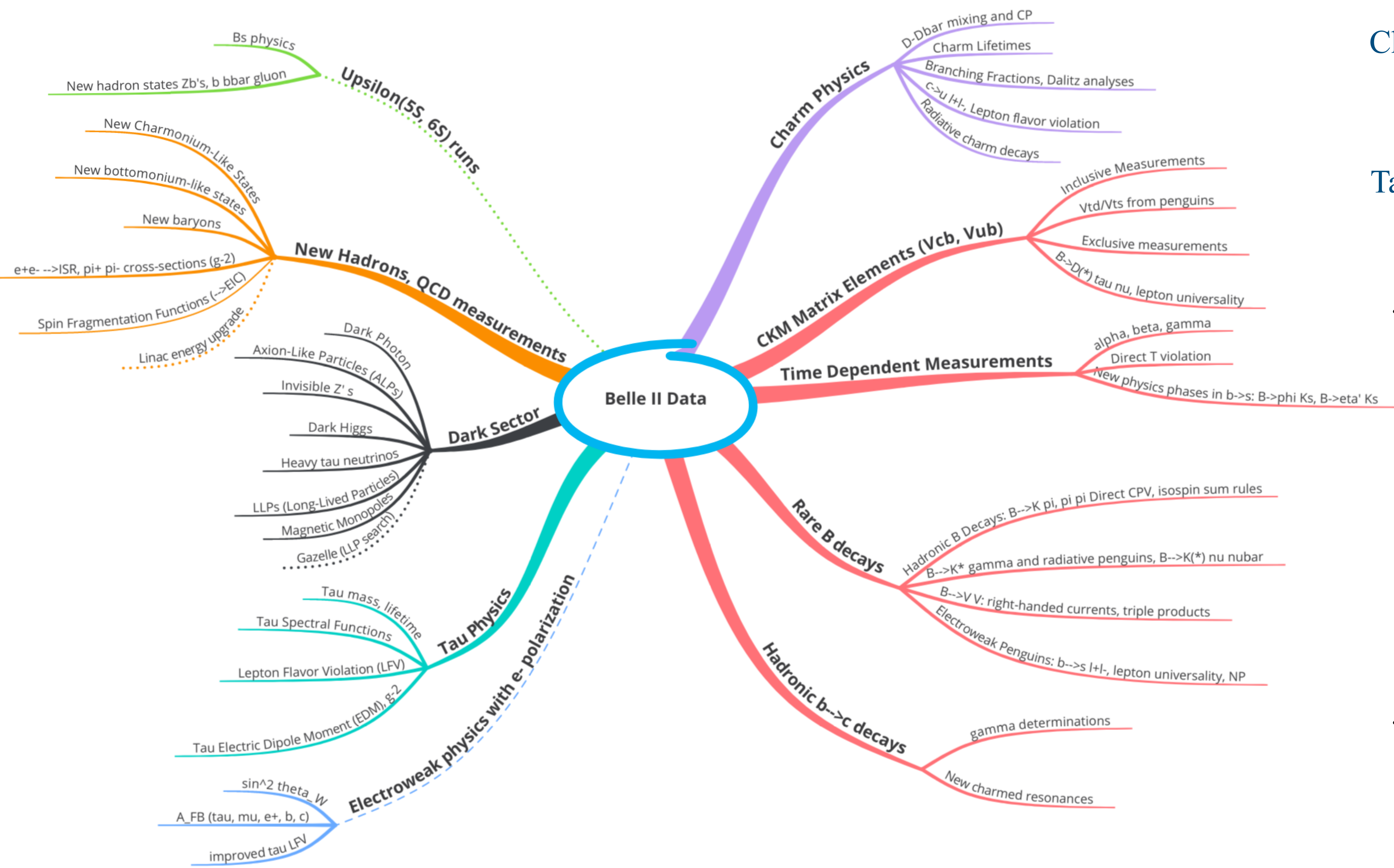
Current status of data taking at Belle II

- Belle II collected data mainly at e^+e^- CM energy of 10.56 GeV
- This CM energy corresponds to the threshold production of $B\bar{B}$ events from $\Upsilon(4S)$ resonance

- Reached a world record of peak intantaneous luminosity of $4.71 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- Recorded total integrated luminosity of $\sim 424\ \mathrm{fb^{-1}}$



Physics programs at Belle II



Charm lifetime measurements

Tagged and Untagged exclusive $|V_{cb}|, |V_{ub}|$

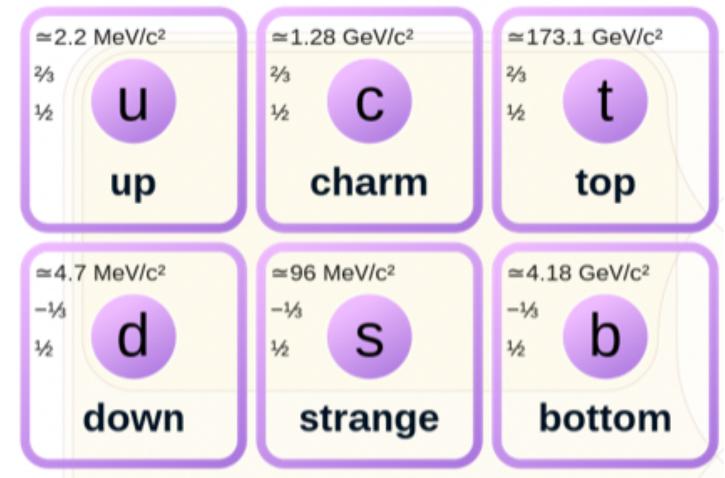
- Isospin sum rule
- α/ϕ_2 measurement
- Three body TDCPV

- EW and Radiative
- LFU

Charm Lifetime measurements

Motivation to study charm

- Charm is the only up type quark whose hadronic weak decays can be analyzed, as the top quark decays much before it can hadronize
- Their lifetime (τ) measurements can be used to 'test' models explaining strong interactions in the charm sector.

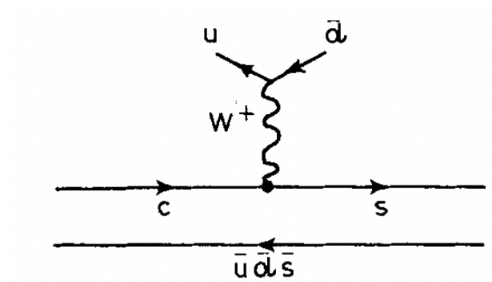


Spectator model term | *Weak Annihilation, Pauli Interference term*

$$\Gamma_{H_Q} = \Gamma_c \left[A_1 + \frac{A_2}{m_c^2} + \frac{A_3}{m_c^3} + \ldots \right]$$

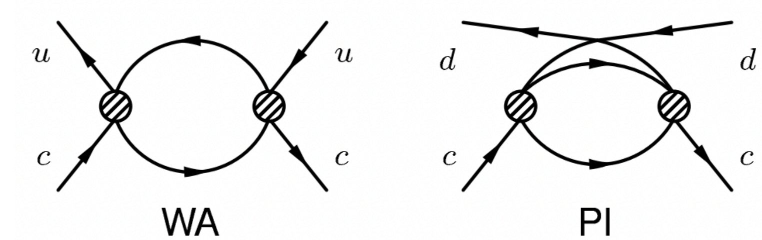
(Heavy Quark Expansion) ($\tau = \hbar \ / \ \Gamma_{total}$)

Lifetime differences among mesons and baryons | *Take spectator quarks into account*



$$\tau(D^+) > \tau(D_s^+) > \tau(\Xi_c^+) > \tau(D^0) > \underline{\tau(\Omega_c^0)} > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$$

- Precise τ measurements are used to calculate partial decay widths from experimentally measured decay fractions.
- Additionally, it can be used to extract Standard Model (SM) parameters ($|V_{cs}|, |V_{cd}|$)



Pre-Belle II status of charm lifetime measurements

Before 2000 (From theoretical predictions)

$\tau(D^+) > \tau(D_s^+) > \tau(D^0) > \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$

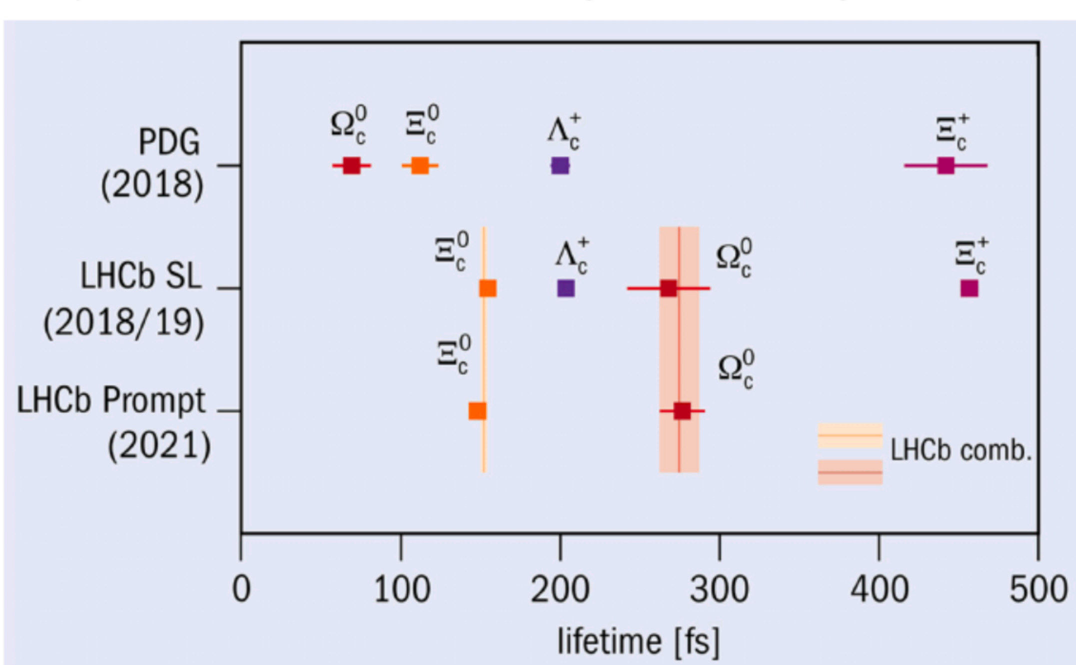
Before 2018 (From experimental measurements)

$\tau(D^+) > \tau(D_s^+) > \tau(\Xi_c^+) > \tau(D^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$

After 2018 (From experimental measurements) (**Emerging**)

$\tau(D^+) > \tau(D_s^+) > \tau(\Xi_c^+) > \tau(D^0) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$

https://cerncourier.com/a/new-charmed-baryon-lifetime-hierarchy-cast-in-stone



Hadron	Lifetimes (fs)	Experiment	Year
D^+	$1039.4 \pm 4.3 \pm 7.0$	FOCUS	2002
D_s^+	$506.4 \pm 3.0 \pm 1.7 \pm 1.7$	LHCb	2017
Ξ_c^+	$456.8 \pm 3.5 \pm 2.9 \pm 3.1$	LHCb	2019
D^0	$409.6 \pm 1.1 \pm 1.5$	FOCUS	2002
Ω_c^0	$268 \pm 24 \pm 10 \pm 2$	LHCb	2018
Λ_c^+	$203.5 \pm 1.0 \pm 1.3 \pm 1.4$	LHCb	2019
Ξ_c^0	$154.5 \pm 1.7 \pm 1.6 \pm 1.0$	LHCb	2019

*First uncertainty is **stat.**, second is **syst.**, third is due to $\tau(D^+)$*

- D^0 and D^+ lifetime measurements are two decades old
- LHCb's measurements are relative and dominated by $\tau(D^+)$ uncertainties

Advantages at Belle II

- Large production cross-section of charm quarks, $\sigma_{c\bar{c}} \sim \sigma_{b\bar{b}}$
- Absolute measurement of lifetimes of all charm hadrons
- e^+e^- provides a 'clean' environment for reconstruction
- Better vertex resolution due to close proximity (1.4cm from IP) of the pixel detector in comparison to Babar and Belle

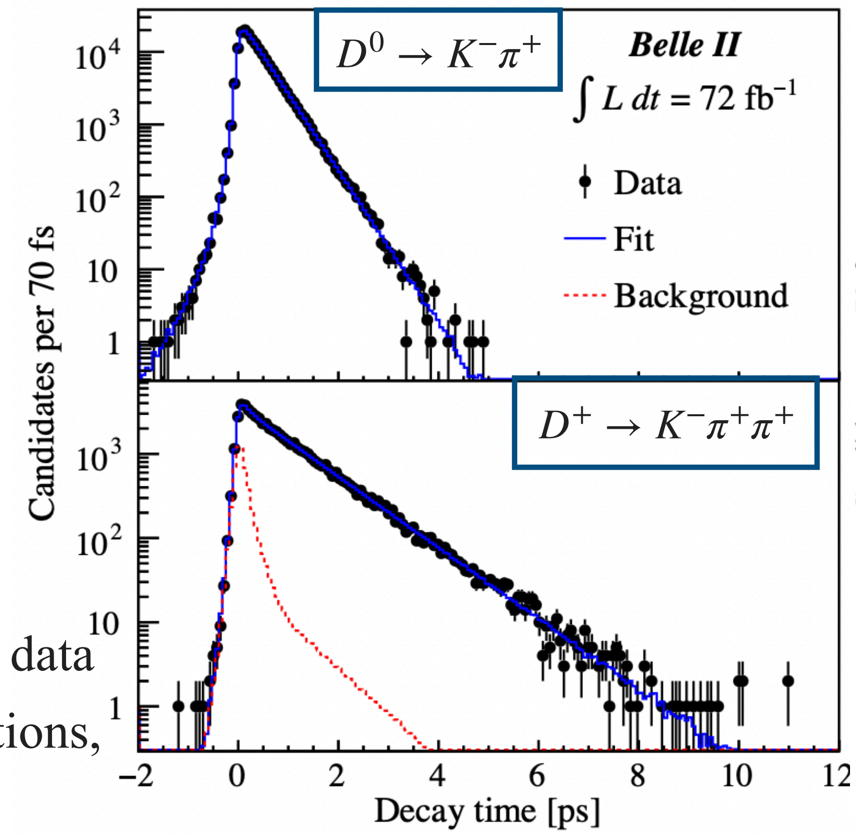
Lifetime measurements of $D^+, D^0, \Lambda_c^+, \Omega_c^0$

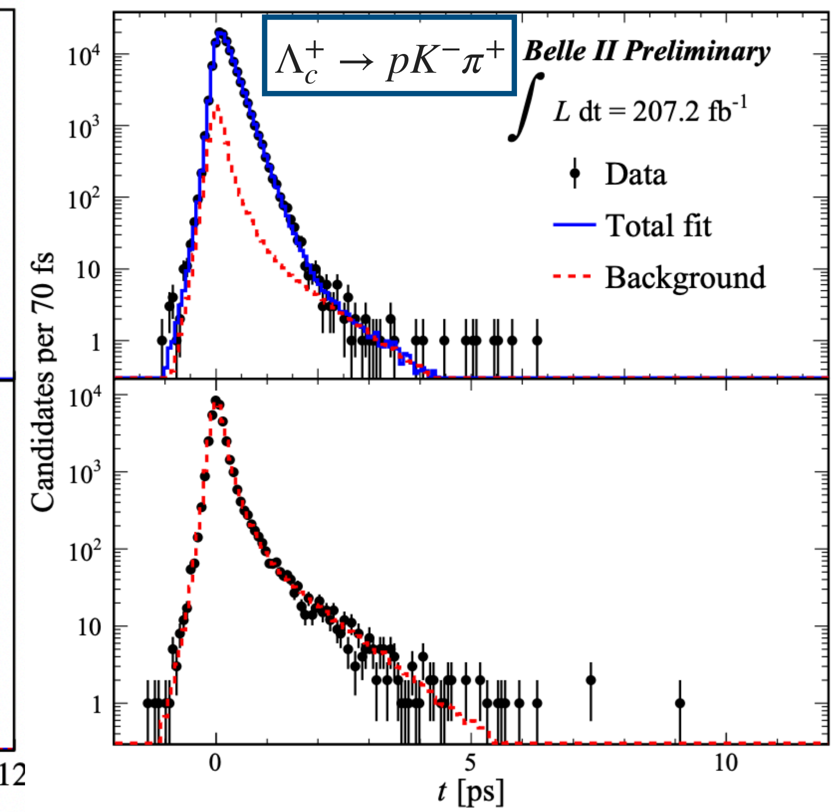
- The hardons are considered from $e^+e^- \to c\bar{c}$ events produced near $\Upsilon(4S)$ resonance
- Lorentz boost provides the separation between the production and decay vertex (d)
- The decay time is calculated using,

$$t_H = \frac{m_H}{p^2}\vec{d}\cdot\vec{p}$$

mass

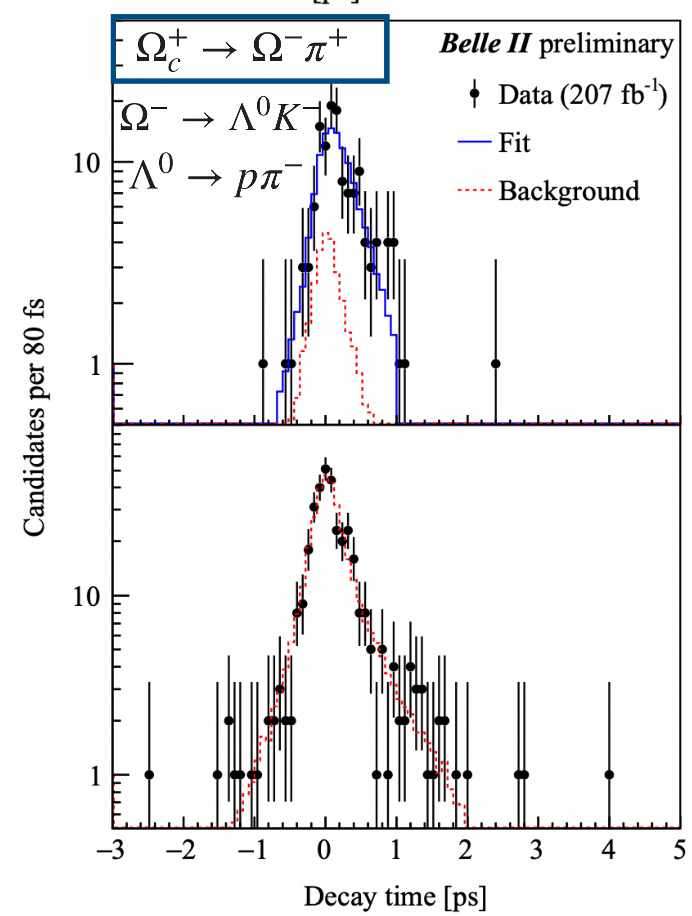
momentum





- Background shapes are determined using side-band data
- The lifetime is extracted from a fit to (t, σ_t) distributions, where σ_t is the uncertainty in t

Hadron	Belle II (fs)	(fs)	References
D^+	$1030.4 \pm 4.7 \pm 3.1$	$1039.4 \pm 4.3 \pm 7.0$ (FOCUS)	PRL 127 211801 (2001)
D^0	$410.5 \pm 1.1 \pm 0.8$	$409.6 \pm 1.1 \pm 1.5$ (FOCUS)	‘’
Ω_c^0	$243 \pm 48 \pm 11$	$268 \pm 24 \pm 10 \pm 2$ (LHCb)	arXiv : 2208.08573v1 (PRD accepted)
Λ_c^+	$203.20 \pm 0.89 \pm 0.77$	$203.5 \pm 1.0 \pm 1.3 \pm 1.4$ (LHCb)	arXiv : 2206.15227v1 (PRL accepted)

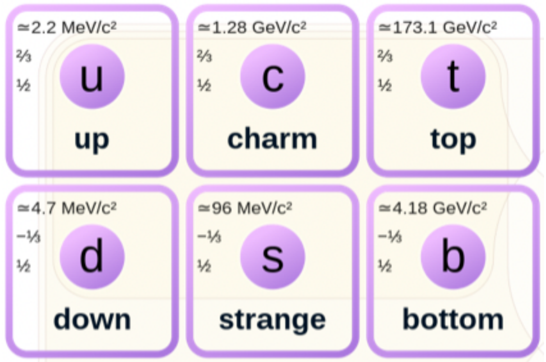


World's precise measurement for D^+, D^0, Λ_c^+ lifetimes !

Confirms Ω_c^0 is not the shortest living charmed baryon !

$|V_{cb}|$ and $|V_{ub}|$ measurements

Cabibbo-Kobayashi-Maskawa (CKM) matrix



$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

CPV

Connecting weak and mass eigenstates

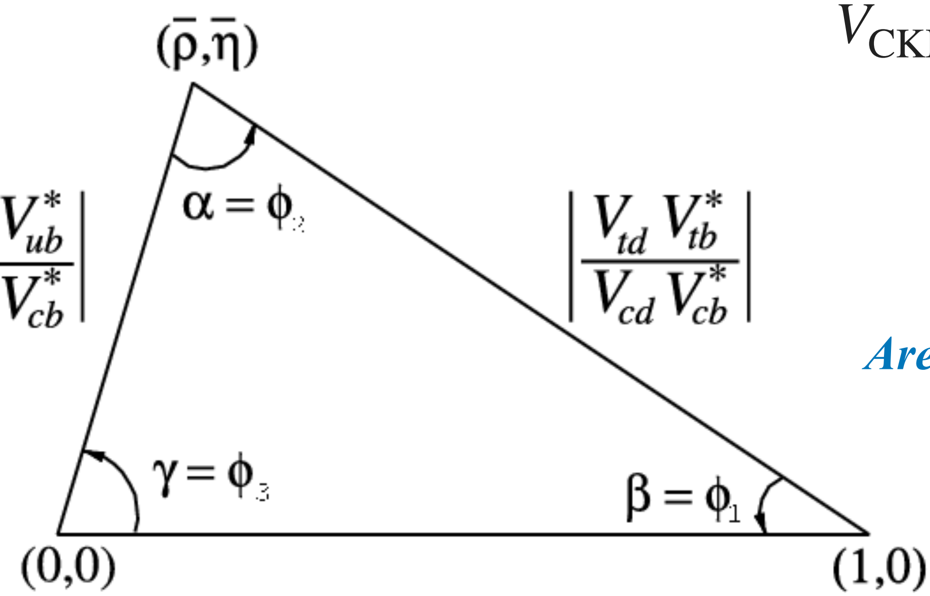
Wolfenstein parametrization

Quark transition	Physics	Experiments
$d \to u$	Nuclear β decay	PIBETA
$s \to u$	Kaon decays	KLOE, KTeV, NA62
$c \to d, s$	Charm decays	CLEO-c, Babar, Belle/Belle II, BESIII
$b \to u, c$	B decays	BaBar, Belle/Belle II, LHCb
$(t \to d, s)$		CDF,DØ
$t \to b$	Top decays	CDF, DØ, ATLAS,CMS

$$\lambda = |V_{us}|/\sqrt{|V_{ud}|^2 + |V_{us}|^2} \qquad \bar\rho + i\bar\eta = -V_{ud}V_{ub}^*/V_{cd}V_{cb}^*$$

$$A\lambda^2 = \lambda |V_{cb}/V_{us}|$$

$$V_{\rm CKM}V_{\rm CKM}^\dagger = I_{3\times3}$$



$$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| \qquad \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$$

Area ∝ CP asymmetry

Measuring the sides of UT

$D_s \to l\nu$

$D \to K l\nu$

$D \to l\nu$

$D \to \pi l\nu$

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$B \to \pi l\nu$

$B \to X_u l\nu$

$B \to D l\nu$

$B \to D^* l\nu$

$B \to X_c l\nu$

$B_d^0 \leftrightarrow \bar B_d^0$

$B_s^0 \leftrightarrow \bar B_s^0$

Overconstrain the Unitarity Triangle by precisely measuring the sides and angles

Present status of $|V_{cb}|$ and $|V_{ub}|$ measurements

arXiv:2206.07501

Inclusive : Sum over all possible hadronic final states ($B \rightarrow X_{c/u}\ l\nu$)

Exclusive : Consider a specific final state ($B \rightarrow (D/D^*/\pi)\ l\nu$)

These measurements are theoretically and experimentally independent !

Type	V_{cb}	V_{ub}
Inclusive	$(42.19 \pm 0.78) \times 10^{-3}$	$(4.19 \pm 0.17) \times 10^{-3}$
Exclusive	$(39.10 \pm 0.50) \times 10^{-3}$	$(3.51 \pm 0.12) \times 10^{-3}$
Deviation	3.3σ	3.3σ

Limitations

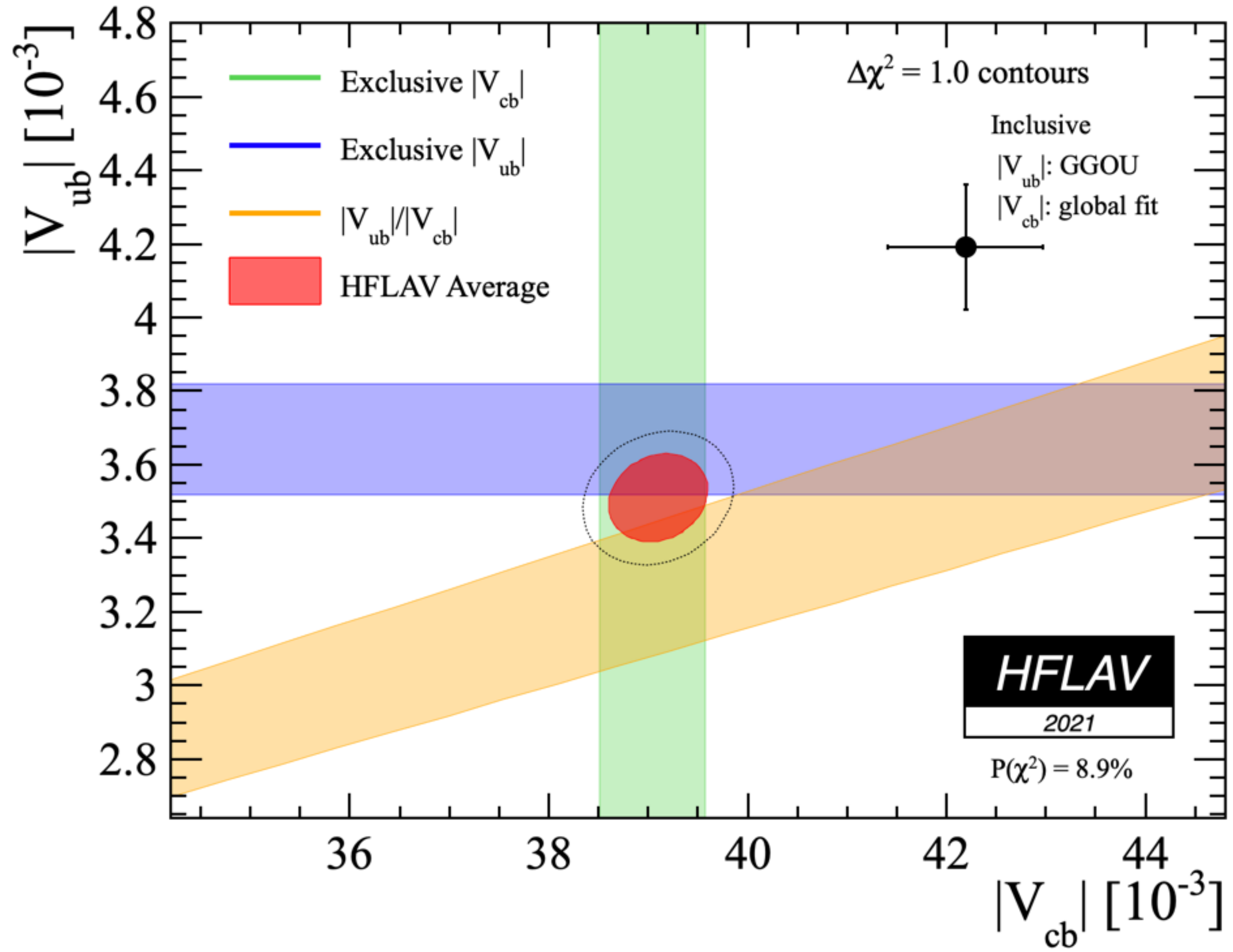
Knowledge of higher order perturbative and non-perturbative terms in HQE (Inclusive)

Knowledge of the hadronic form factors (Exclusive)

Complementary measurements are important !

Apart from, constraining the UT triangle,

- V_{cb} and V_{ub} values are determined from tree level processes, assuming no new physics (NP)contributions
- These values are then used to make SM predictions for loop level processes which are sensitive to new physics (NP)



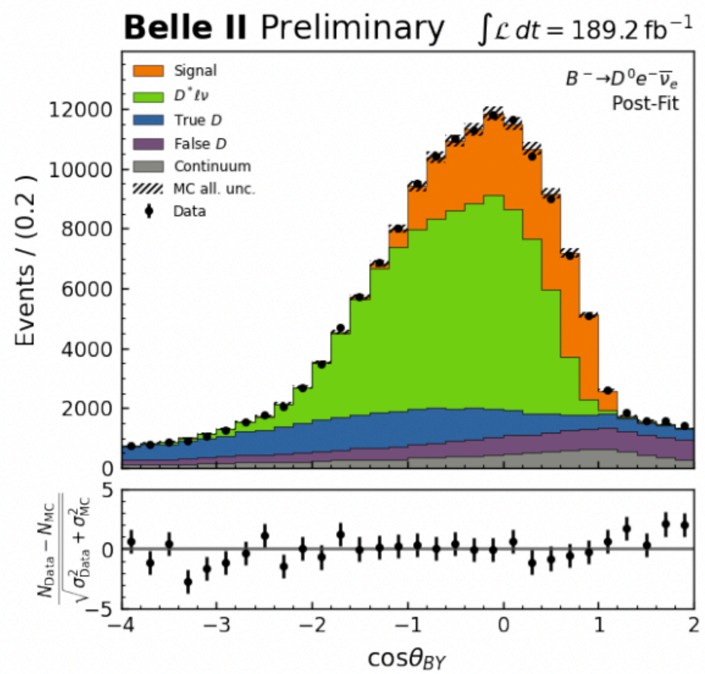
Untagged $|V_{cb}|$ measurement: $B \to Dl\nu$

Analysis strategy

- Signal: $B \to Dl\nu$ $(B^0 \to D^- l^+ \nu, B^+ \to \bar{D}^0 l^+ \nu)$
- $D^- \to K^+\pi^-\pi^-, D^0 \to K^+\pi^-, l = e, \mu$

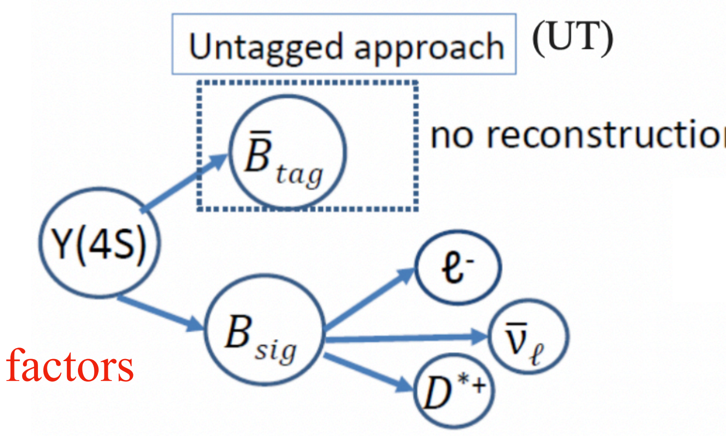
Signal extraction: Angle between B and Dl $(cos\theta_{BY})$

- Continuum is the dominant: Continuum Suppression
- Other backgrounds of conceren are: other B decays, $B \to D^* l\nu$
- Use D^* veto to reject these backgrounds

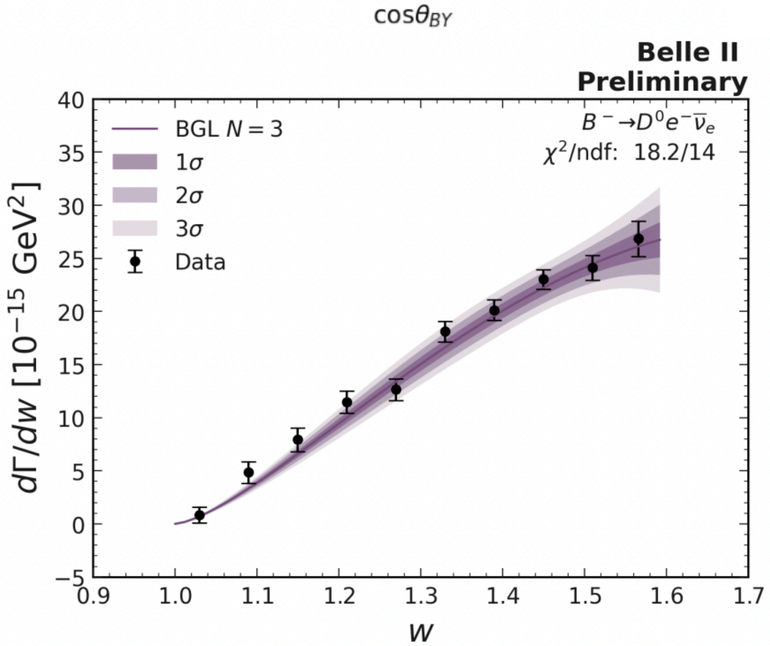


$$\frac{d\Gamma(B \to D\ell\nu_\ell)}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2 (w^2 - 1)^{3/2} \eta_{EW}^2 \mathcal{G}^2(w) |V_{cb}|^2$$

product of 4-mom of B and D — Electroweak corrections — contain form factors



High efficiency/Low purity



Extraction of $|V_{cb}|$

- The partial decay rates are extracted in bins of w by performing a combined fit to the BGL expression and QCD form factors

ICHEP 2022

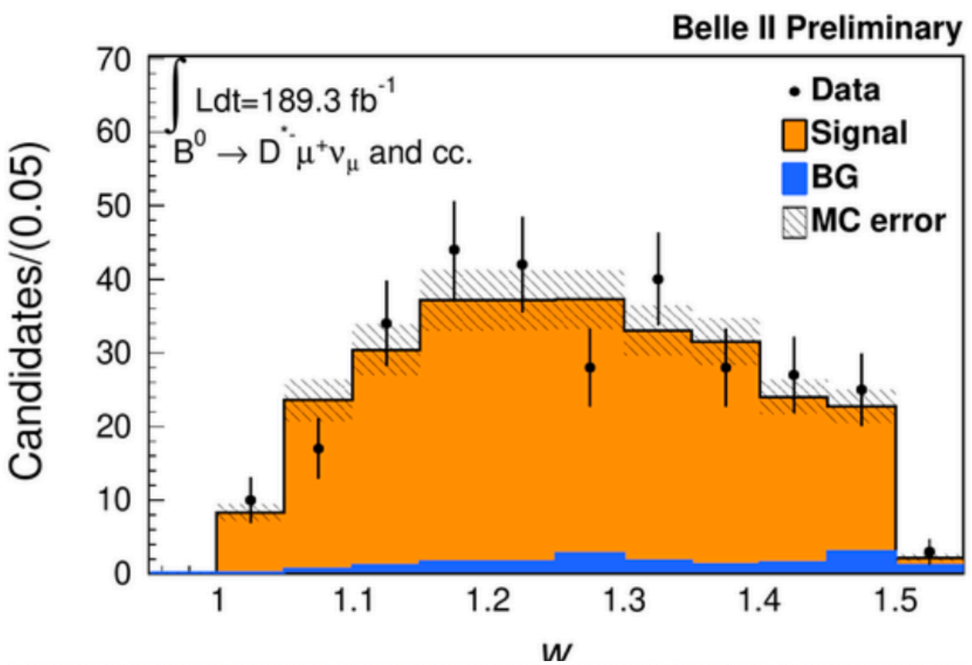
$$\eta_{EW} |V_{cb}| = (38.53 \pm 1.15) \times 10^{-3}$$

stat. + syst. + theoretical

Consistent with exclusive world average values !

Tagged $|V_{cb}|$ measurement: $B \to D^* l \nu$

- Signal: $B \to D^* l \nu$ ($B^0 \to D^{*-} l^+ \nu$)
- $D^{*-} \to \bar{D}^0 \pi^-, D^0 \to K^+ \pi^-, l = e, \mu$
- Reconstruction of low momentum pions from D^* is challenging
- FEI using HT algorithm to identify B_{tag} candidates



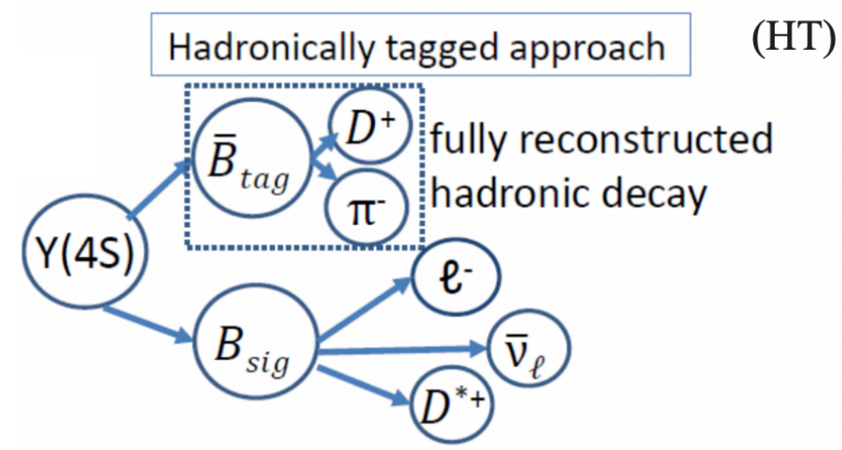
$$\frac{d\Gamma}{dw} = \frac{\eta_{\text{EW}}^2 G_F^2}{48\pi^3} m_{D^*}^3 (m_B - m_{D^*})^2 g(w) F^2(w) |V_{cb}|^2$$

product of 4-mom of B and D

contain form factors

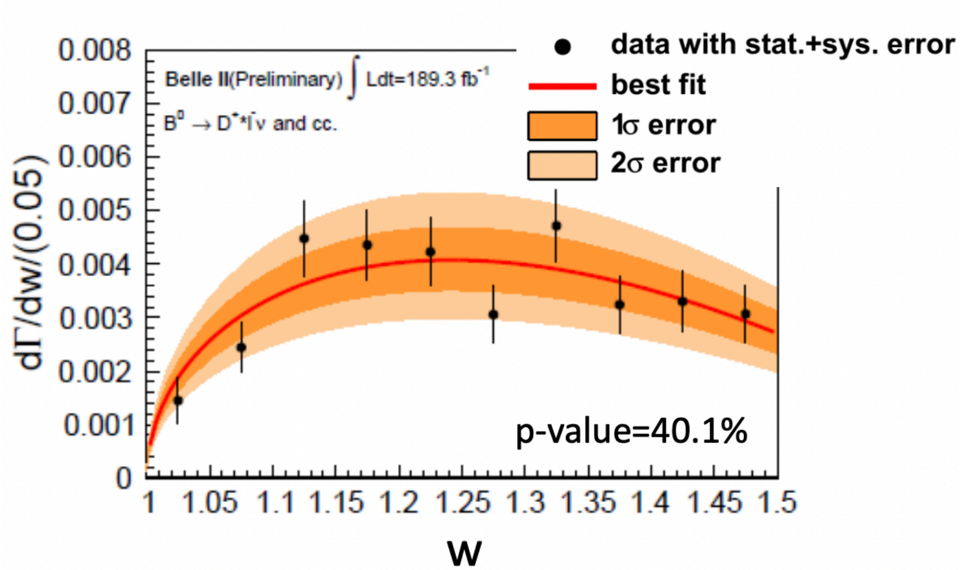
Low efficiency/High purity

(HT)



Extraction of $|V_{cb}|$

- The partial decay rates are extracted in bins of w by performing a combined fit to the CLN expression and QCD form factors



MORIOND 2022

$$\eta_{\text{EW}} |V_{cb}| = (38.2 \pm 2.8) \times 10^{-3}$$

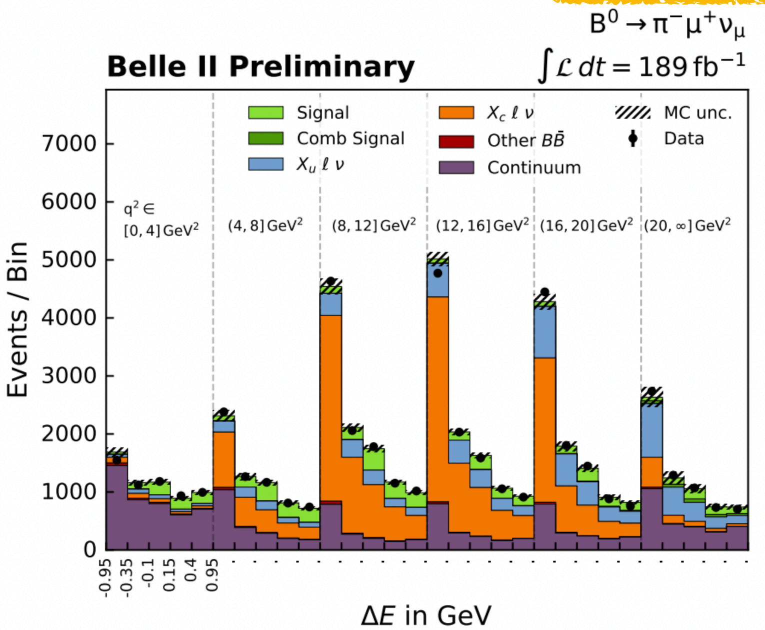
stat. + syst. + theoretical

Consistent with exclusive world average values !

Untagged $|V_{ub}|$ measurement: $B \to \pi l \nu$

- Signal: $B \to \pi l \nu$ ($B^0 \to \pi^{\pm} l^{\mp} \nu$), $l = e, \mu$
- Everything else including the other B is included as the rest-of-events to determine p_{ν}
- Continuum is the dominant: Continuum Suppression (BDT)
- Other backgrounds of concern are: other B

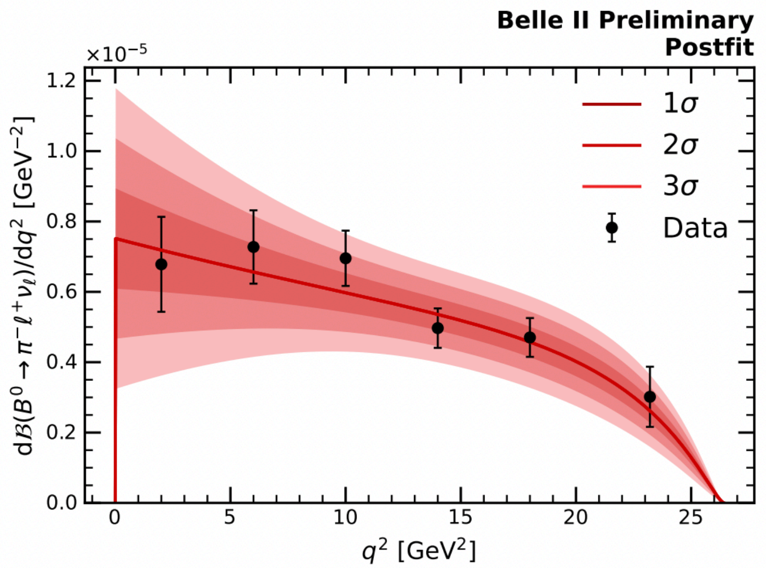
Signal extraction: $M_{\rm bc} = \sqrt{E^{*2}_{\rm beam} - p^{*2}_{B}}$ and $\Delta E = E^{*}_{B} - E^{*}_{\rm beam}$



$$\frac{d\Gamma(B \to \pi l \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |p_\pi|^3 |f_+(q^2)|^2$$

$M(l\bar{l})$

form factor



Extraction of $|V_{ub}|$

- The partial decay rates are extracted in bins of q^2 by performing a combined fit to the BCL expression and QCD form factor

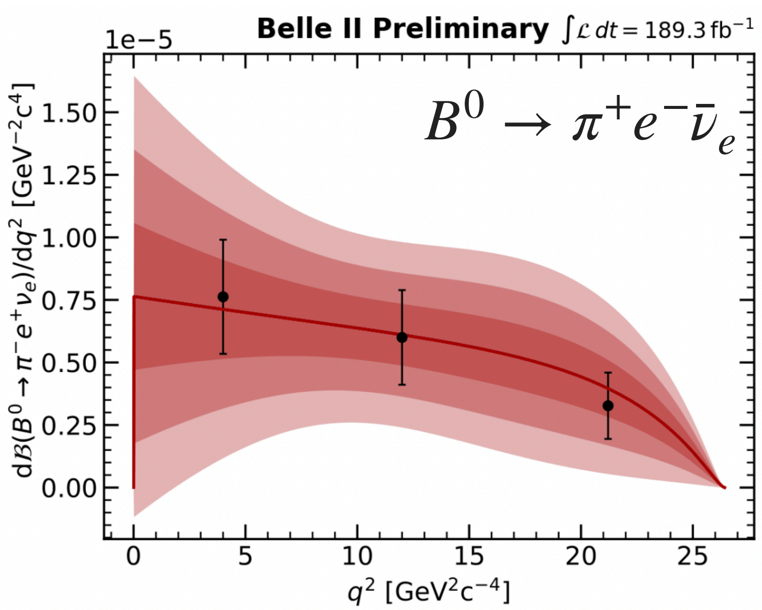
ICHEP 2022

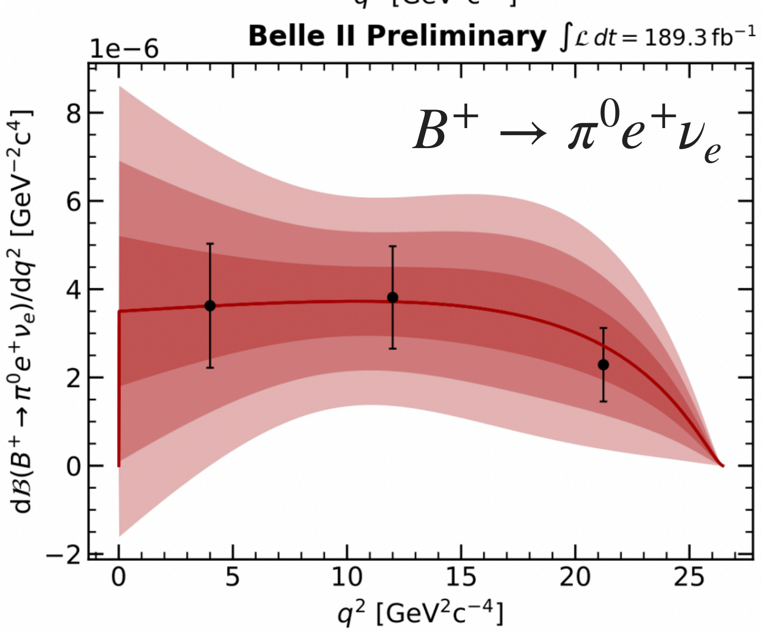
$$|V_{ub}|_{B^0 \to \pi^- l^+ \nu_l} = (3.54 \ \pm\ 0.12_{\rm stat.} \ \pm 0.15_{\rm syst.} \ \pm 0.16_{\rm theo.}) \times 10^{-3}$$

Consistent with exclusive world average values !

Tagged $|V_{ub}|$ measurement: $B \to \pi e \nu$

- Signal: $B \to \pi e \nu$ ($B^0 \to \pi^+ e^- \bar{\nu}_e, B^+ \to \pi^0 e^+ \nu_e$)
- FEI using HT algorithm to identify B_{tag} candidates
- MC simulations are considered for background studies
- Cross-feeds: $B^0 \to \rho^- l^+ \nu_l$
- Continuum backgrounds, generic $B\bar{B}$, and $B \to X_u l \nu$





Signal extraction: $M^2_{miss} \equiv p^2_{miss} = (p_{B_{sig}} - p_{e\pi})^2$

$$\frac{d\Gamma(B \to \pi l \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |p_\pi|^3 |f_+(q^2)|^2$$

$M(l\bar{l})$

contain form factors

Extraction of $|V_{cb}|$

- The partial decay rates are extracted in bins of q^2 by performing a combined fit to the BCL expression and QCD form factors

arXiv:2206.08102

$$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$$

stat. + syst. + theoretical

Consistent with exclusive world average values !

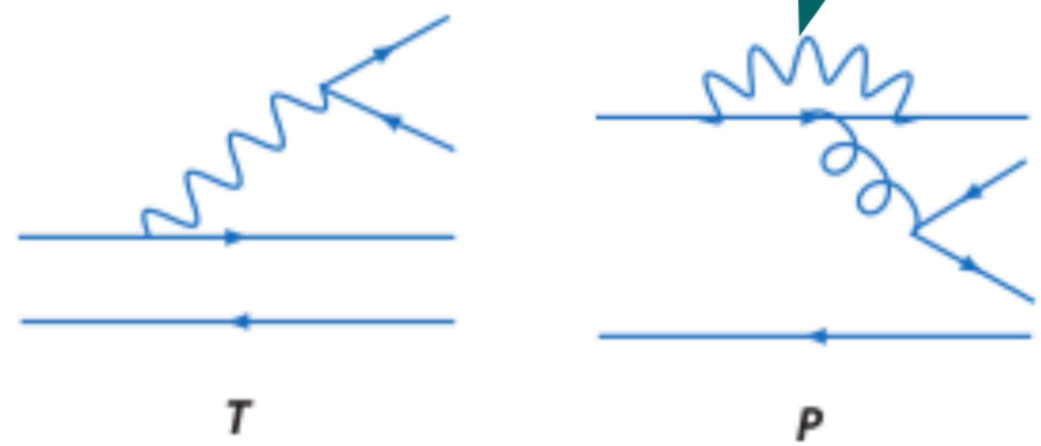
Rare B meson / Charmless B decays

u	c	t
d	s	b

b $\not\to$ c

BF $\leq$ (10^{-5})

Quark transition	Remarks
$b \to u$	Tree level (but suppressed)
$b \to d$	via u, c, t, X
$b \to s$	via u, c, t, X



Why go charmless ?

- Good place to look for non-SM physics (in general)
- Verify Isospin sum rule
- Determination of Φ_2 / α
- Measure CP asymmetry

} Belle II charmless Physics goals

Ways of going charmless ?

- Two body decays ($B \to \pi\pi$, $B \to K\pi$)
- Quasi-two body decays ($B \to \rho\pi$, $B \to \rho\rho$)
- Multibody body decays ($B \to KKK$)

Belle II can access all of these !

Two and three body B decay First reconstructions/ measurements at Belle II

Charmless B decays : Phenomenology

Isospin sum rule in $K\pi$ decay channels

Assuming isospin symmetry in the dominant Feynman diagrams (QCD penguin),

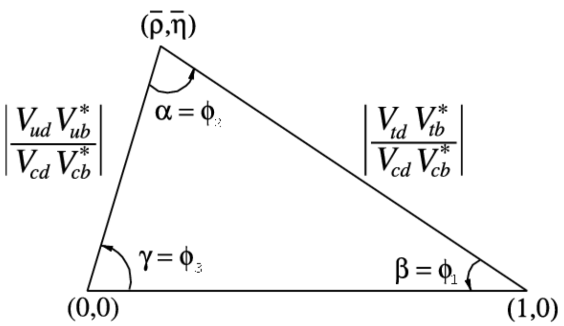
$$\Gamma(K^+\pi^-) \approx \Gamma(K^0\pi^+) \approx 2\Gamma(K^+\pi^0) \approx 2\Gamma(K^0\pi^0)$$

$$\mathcal{A}_{\rm CP}(K^+\pi^-) + \mathcal{A}_{\rm CP}(K^0\pi^+) \approx \mathcal{A}_{\rm CP}(K^+\pi^0) + \mathcal{A}_{\rm CP}(K^0\pi^0)$$

Isospin sum rule in terms of CP asymmetries

In SM, $I_{K\pi} = 0$

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$



Determination of α/ϕ_2 using $\pi\pi$ decay channels

Extraction of α/ϕ_2 is complicated by the presence of tree and penguin diagrams.

- To disentangle them, an isospin analysis is necessary which requires precision measurement of the $\mathcal{B}$ and CP asymmetry.

Direct CP asymmtery determination using three body decays

- Dalitz decays are useful to understand the relative contribution of tree and penguin amplitudes.

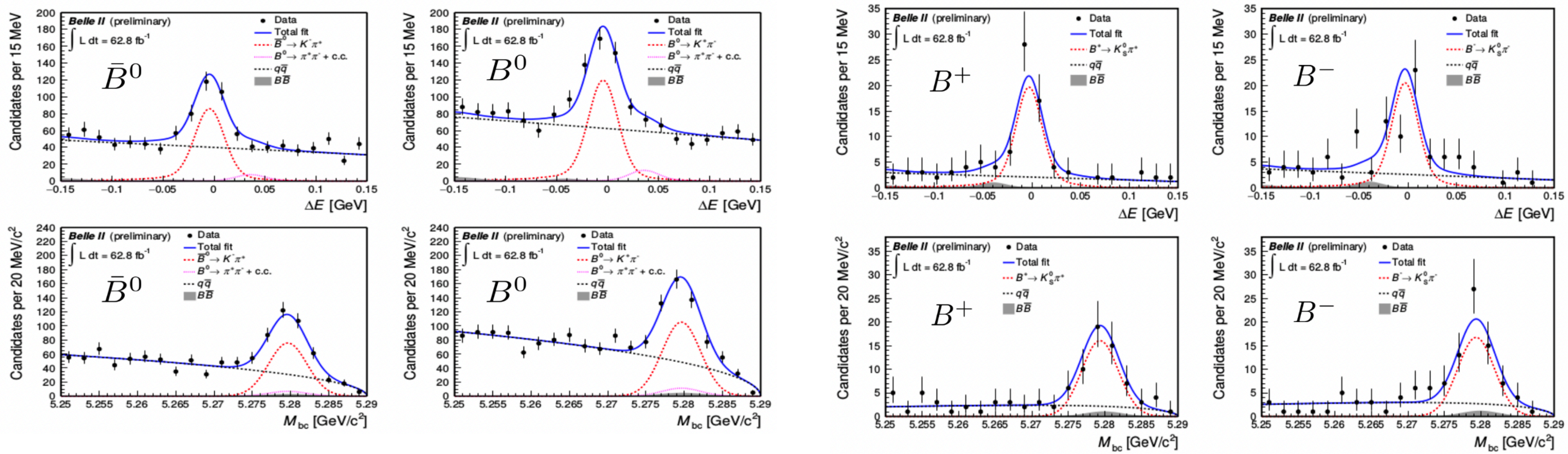
- Moreover, they are good places to look for direct CP asymmetries.

Belle II provides unique oppurtunity to measure all these decays consistently !

Isospin analysis

Isospin sum rule : $B^0 \rightarrow K^+\pi^-$ and $B^+ \rightarrow K^0\pi^+$ $\quad 62.8\ \text{fb}^{-1}$

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$



$B^0 \rightarrow K^+\pi^-$

Quantity	Belle II [69M $B\bar{B}$]	Belle [85M $B\bar{B}$]
	arXiv:2106.03766v1	**PRD 69, 111102 (2004)**
$\mathcal{B}$	$(18.0 \pm 0.9(\text{stat.}) \pm 0.9(\text{syst.})) \times 10^{-6}$	$(18.5 \pm 1.0(\text{stat.}) \pm 0.7(\text{syst.})) \times 10^{-6}$
$\mathcal{A}$	$-0.16 \pm 0.05(\text{stat.}) \pm 0.01(\text{syst.})$	–

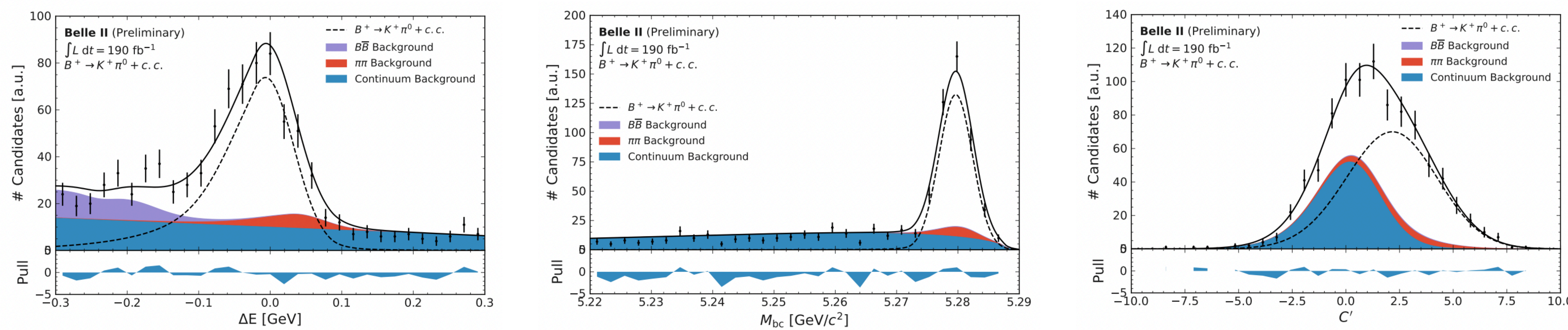
$B^+ \rightarrow K^0\pi^+$

Quantity	Belle II [69M $B\bar{B}$]	Belle [85M $B\bar{B}$]
	arXiv:2106.03766v1	**PRD 69, 111102 (2004)**
$\mathcal{B}$	$(21.4^{+2.3}_{-2.2}(\text{stat.}) \pm 1.6(\text{syst.})) \times 10^{-6}$	$(22.0 \pm 1.9(\text{stat.}) \pm 1.1(\text{syst.})) \times 10^{-6}$
$\mathcal{A}$	$-0.01 \pm 0.08(\text{stat.}) \pm 0.05(\text{syst.})$	–

Consistent with previous Belle measurement

Isospin sum rule : $B^+ \to K^+\pi^0$ 190 fb^{-1}

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$



- An updated measurement with a better fit strategy : 3D fit
- Validation of analysis procedure: $B^0 \to \bar{D}(\to K^+\pi^-)\pi^0$
- Use of off-resonance data and control mode: shift and scaling parameter

$$\mathcal{A}_{CP} = \frac{N(B^+) - N(B^-)}{N(B^+) + N(B^-)}$$

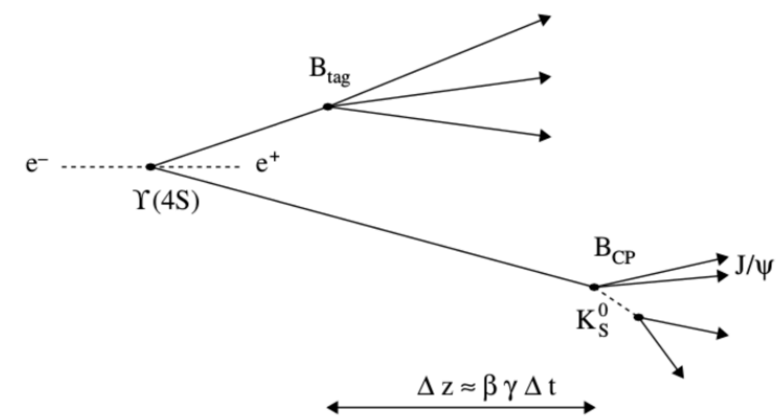
Parameter	Belle II (~197 M BB pairs) arXiv:2209.05154	Belle (449 M BB pairs) PRL 99 121601 (2007)
$\mathscr{B}(B^+ \to K^+\pi^0)$	$(14.30 \pm 0.69 \pm 0.79) \times 10^{-6}$	$(12.4 \pm 0.5 \pm 0.6) \times 10^{-6}$
$\mathscr{A}_{CP}$	$0.014 \pm 0.047 \pm 0.010$	-

First uncertainty: stat.; second: syst.

Within 1.5σ of the previous Belle result even with 2.3 times less statistics

Flavor tagging at Belle II

- B_{tag} is reconstructed from (after applying selection criteria in ROE events) inclusive B decays.
- They are so chosen that the flavor of the B_{tag} (B or $\bar{B}$) can be determined. Eg. $B^0 \to X^- l^+ \nu$
- They are not 100% efficienct in correctly identifying the flavor of B_{tag}.
- Hence, dilution factors are introduced to quantify the mistag probability (w).

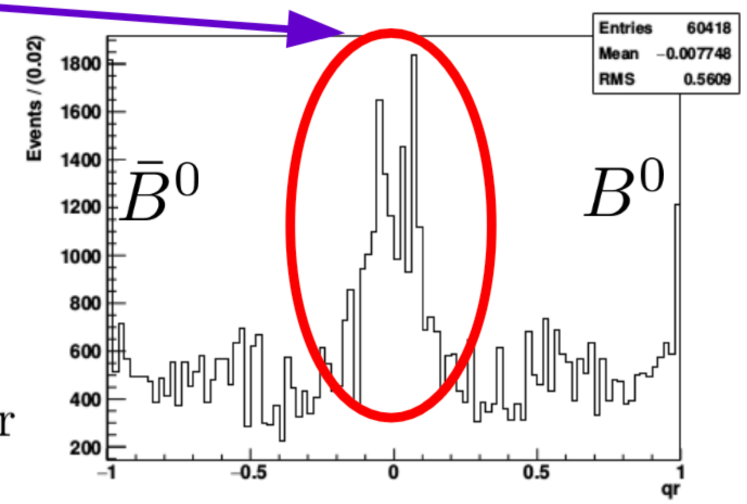


Output of the Flavor Tagger

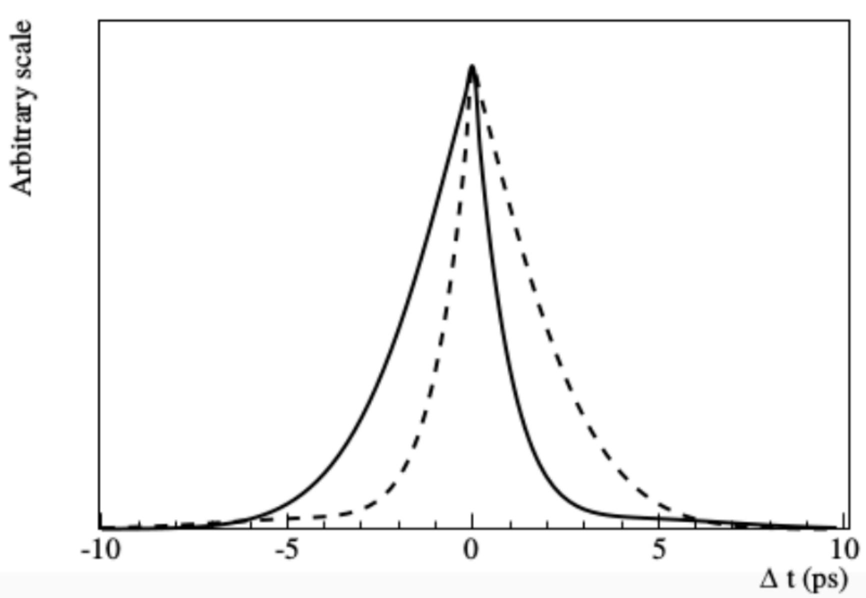
$$\text{q} \in [+1(B^0),\ -1(\bar{B}^0)]$$
$$\text{r} = (1 - 2w)$$

$B_{\text{rec}}/B_{\text{CP}}/B_{\text{sig}}$

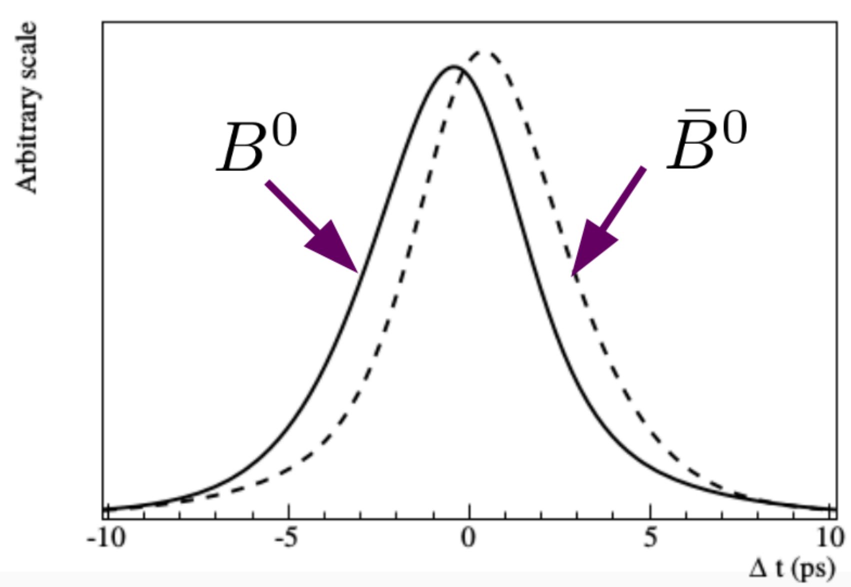
No flavor info.



Perfect reconstruction



Resolution effects + Dilution factor



EPJ C 82 4 (2007)

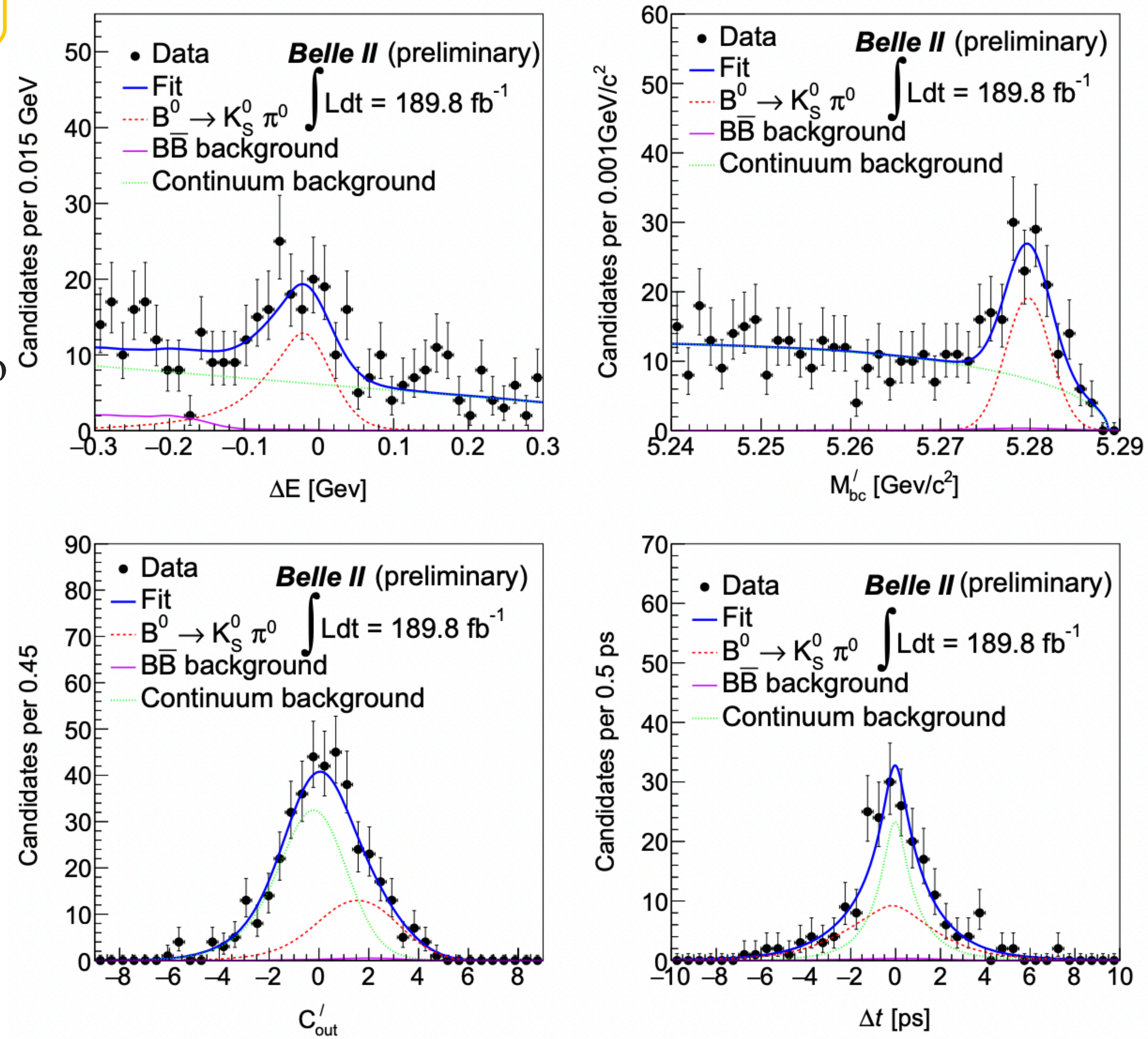
$$\epsilon_{eff} = (28.8 \pm 1.2\ (\text{stat.}) \pm 0.4\ (\text{syst.}))\ \%$$

Isospin sum rule : $B^0 \to K^0\pi^0$ 190 fb^{-1}

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

arXiv: 2206.07453v1

- Fit strategy: 4D fit
- Challenging $B^0 \to K_s^0\pi^0$ decay vertex reconstruction
- Continuum is the dominant background
- Use of Belle II flavor tagging algorithm to measure Δt to enhance the sensitivity to $\mathscr{A}_{CP}$
- First measurement of $\mathscr{A}_{CP}$ in $B^0 \to K_s^0\pi^0$ to use time-dependent analysis.



Experiment	Values
Belle II (197 M BB pairs)	$\mathscr{B} = (11.0 \pm 1.2 \pm 1.0) \times 10^{-6}$ $\mathscr{A}_{CP} = -0.41^{+0.30}_{-0.32} \pm 0.09$
Belle (449 M BB pairs)	$\mathscr{B} = (9.2 \pm 0.7 \pm 0.6) \times 10^{-6}$

First uncertainty: stat.; second: syst. **PRL 99 121601 (2007)**

Consistent with previous Belle measurement !

α/ϕ_2 determination

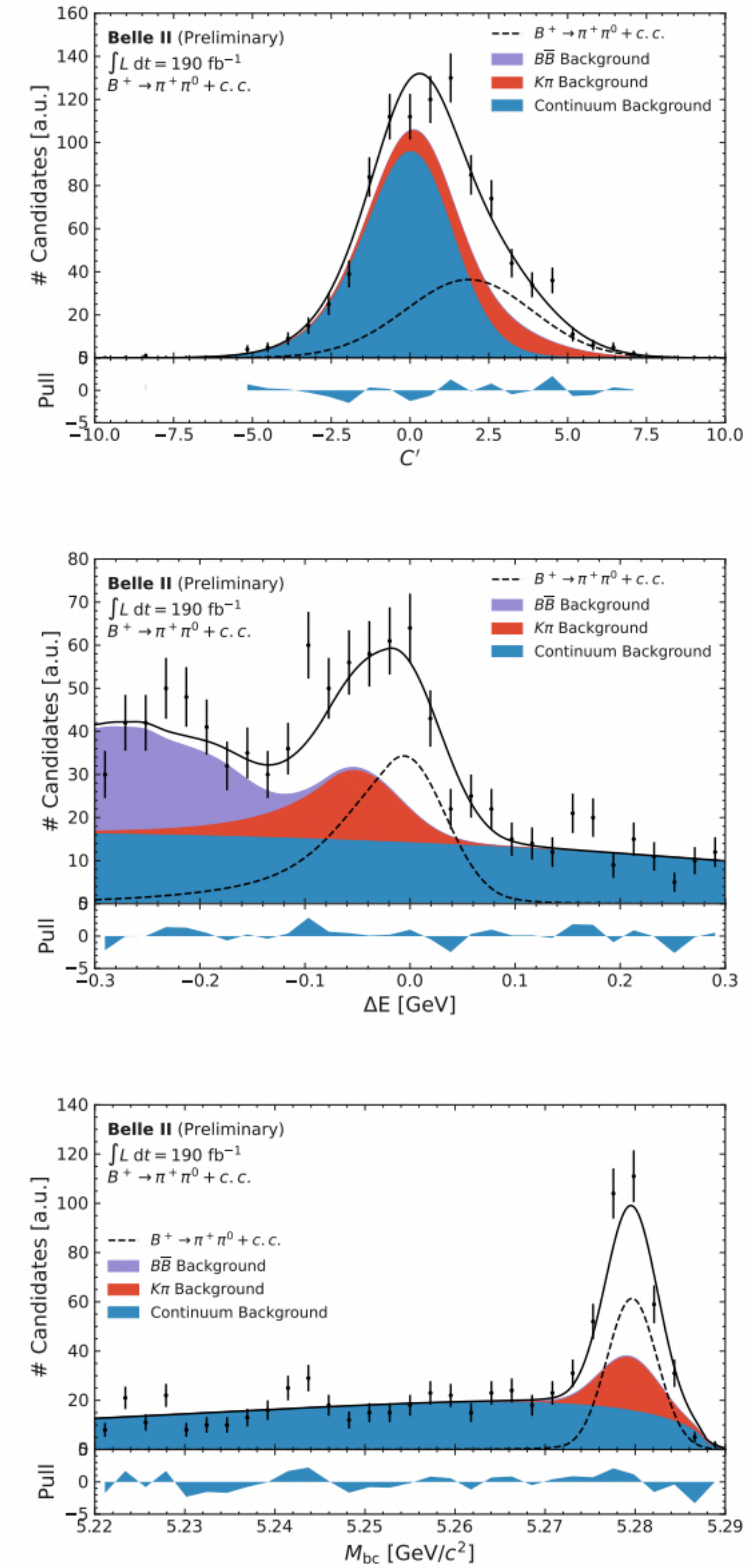
α/ϕ_2 determination: $B \to \pi\pi$ / $B \to \rho\rho$

- Target: Measurement of $\mathcal{B}$ and $\mathcal{A}_{CP}$
- Process mediates via $b \to u$ diagrams
- Interference between 'tree' and 'penguin' diagrams

$$B^0 \to \pi^+\pi^- \qquad B^0 \to \rho^+\rho^-$$
$$B^0 \to \pi^0\pi^0 \quad \text{or,} \quad B^0 \to \rho^0\rho^0$$
$$B^+ \to \pi^+\pi^0 \qquad B^+ \to \rho^+\rho^0$$

- Multivariate analysis to suppress continuum
- 3D signal extraction function
- Validation of analysis procedure: $B^+ \to \bar{D}(\to K^+\pi^-\pi^0)\pi^+$

$B^+ \to \pi^+\pi^0$



	ICHEP 2022	**PRL 99 121601 (2007)**
Parameter	Belle II (~197 M BB pairs)	Belle (449 M BB pairs)
$\mathcal{B}(B^+ \to \pi^+\pi^0)$	$(6.12 \pm 0.53 \pm 0.53) \times 10^{-6}$	$(6.5 \pm 0.4 \pm 0.4) \times 10^{-6}$
$\mathcal{A}_{CP}$	$-0.085 \pm 0.085 \pm 0.019$	-

First uncertainty: stat.; second: syst.

Consistent with previous Belle measurement !

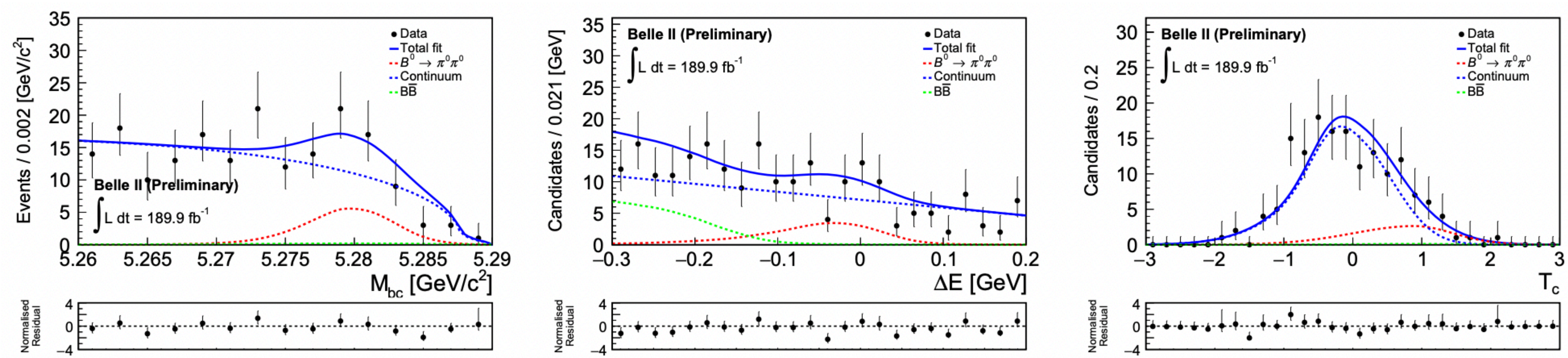
α/ϕ_2 determination: $B^0 \to \pi^0\pi^0$

- Feasible only at e^+e^- colliders like Belle II
- Very challenging due to neutral final states

$$\mathcal{A}_{CP} = \frac{\Gamma(\bar{B} \to \pi^0\pi^0) - \Gamma(B \to \pi^0\pi^0)}{\Gamma(\bar{B} \to \pi^0\pi^0) + \Gamma(B \to \pi^0\pi^0)}$$

Analysis strategy

- Photons for signal reconstruction are selected via BDT
- 2D KDE function for signal extraction
- As is evident, continuum is the dominant background
- Use of data driven method for continuum suppression
- Use of Belle II flavor tagging algorithm
- Validation of analysis procedure: $B^0 \to D(\to K^+\pi^-\pi^0)\pi^0$



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PRD 96 032007 (2017)

Parameter	Belle II (~197 M BB pairs)	Belle (771 M BB pairs)
$\mathcal{B}(B^0 \to \pi^0\pi^0)$	$(1.32 \pm 0.25 \pm 0.18) \times 10^{-6}$	$(1.31 \pm 0.19 \pm 0.19) \times 10^{-6}$
$\mathcal{A}_{CP}$	$+0.14 \pm 0.46 \pm 0.07$	$+0.14 \pm 0.36 \pm 0.10$

First uncertainty: stat.; second: syst.

Comaprable sensitivity with 1/4th of data!

α/ϕ_2 determination: $B^0 \to \rho^+\rho^-$

- 'Golden' channel for ϕ_2 measurement: small contribution from 'penguin' diagram
- Relies on the excellent neutral performance of the Belle II detector
- Target: $\mathscr{B}$ and polarization

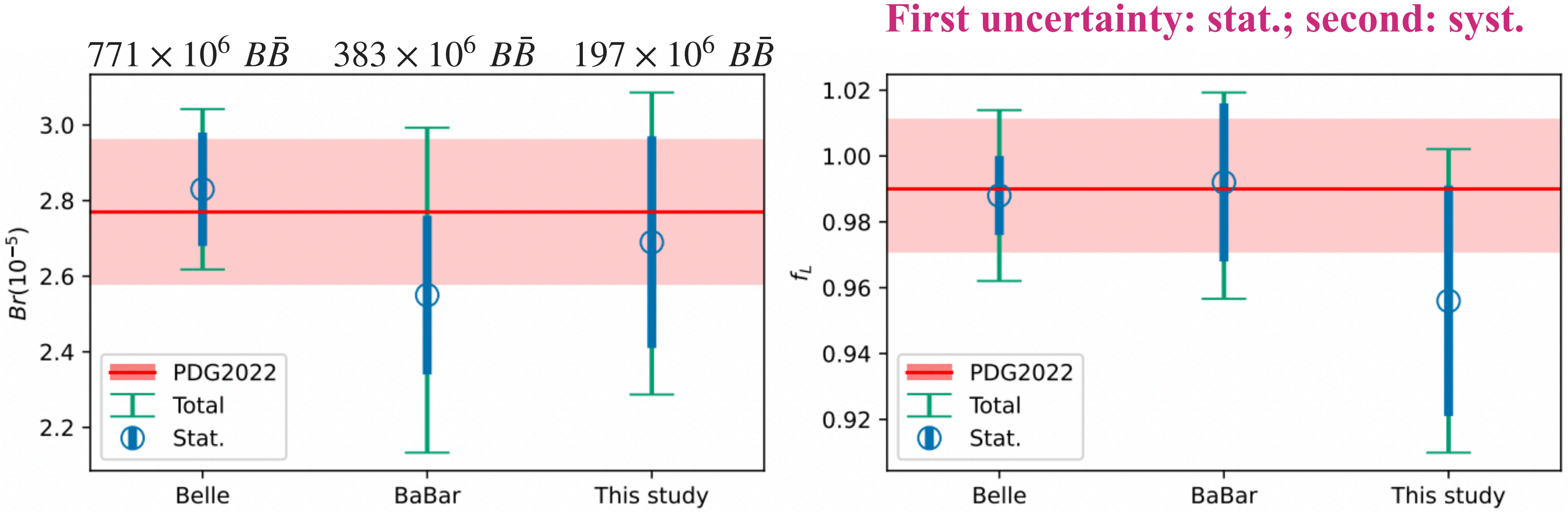
Analysis strategy

- 6D fit is performed to extract the yields
- Continuum and peaking background (with similar final state) complicates the analysis
- Validation: analysis procedure and continuum suppression inputs

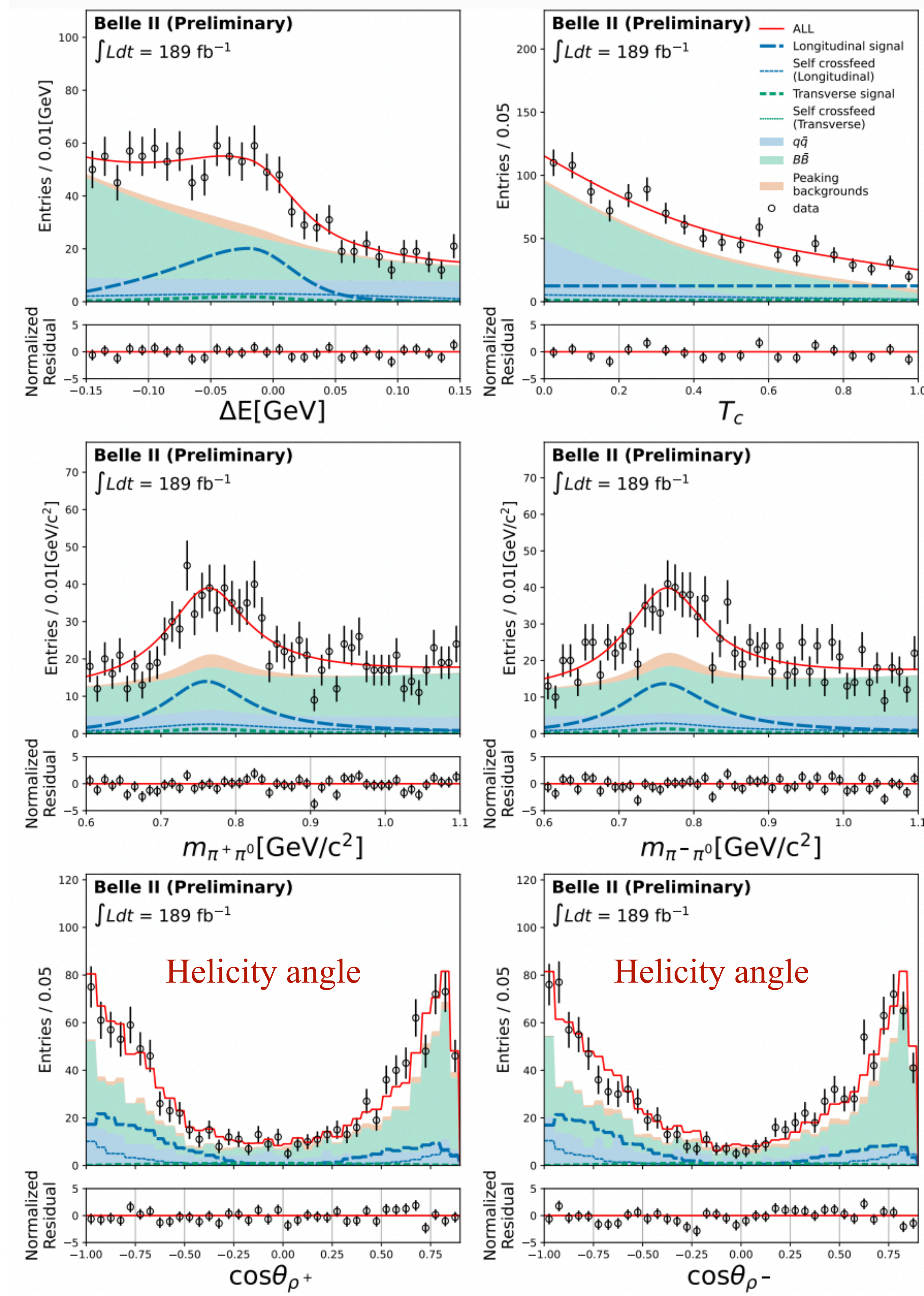
arXiv: 2208.03554v1

$$\mathscr{B} = (2.67 \ \pm 0.28 \ \pm 0.28) \times 10^{-5}$$
$$f_L = 0.956 \ \pm 0.035 \ \pm 0.033$$

First uncertainty: stat.; second: syst.



Consistent with previous measurements



α/ϕ_2 determination: $B^+ \to \rho^+\rho^0$

- Relies on the excellent neutral performance of the Belle II detector
- Target: $\mathscr{B}$, $\mathscr{A}_{CP}$, and polarization

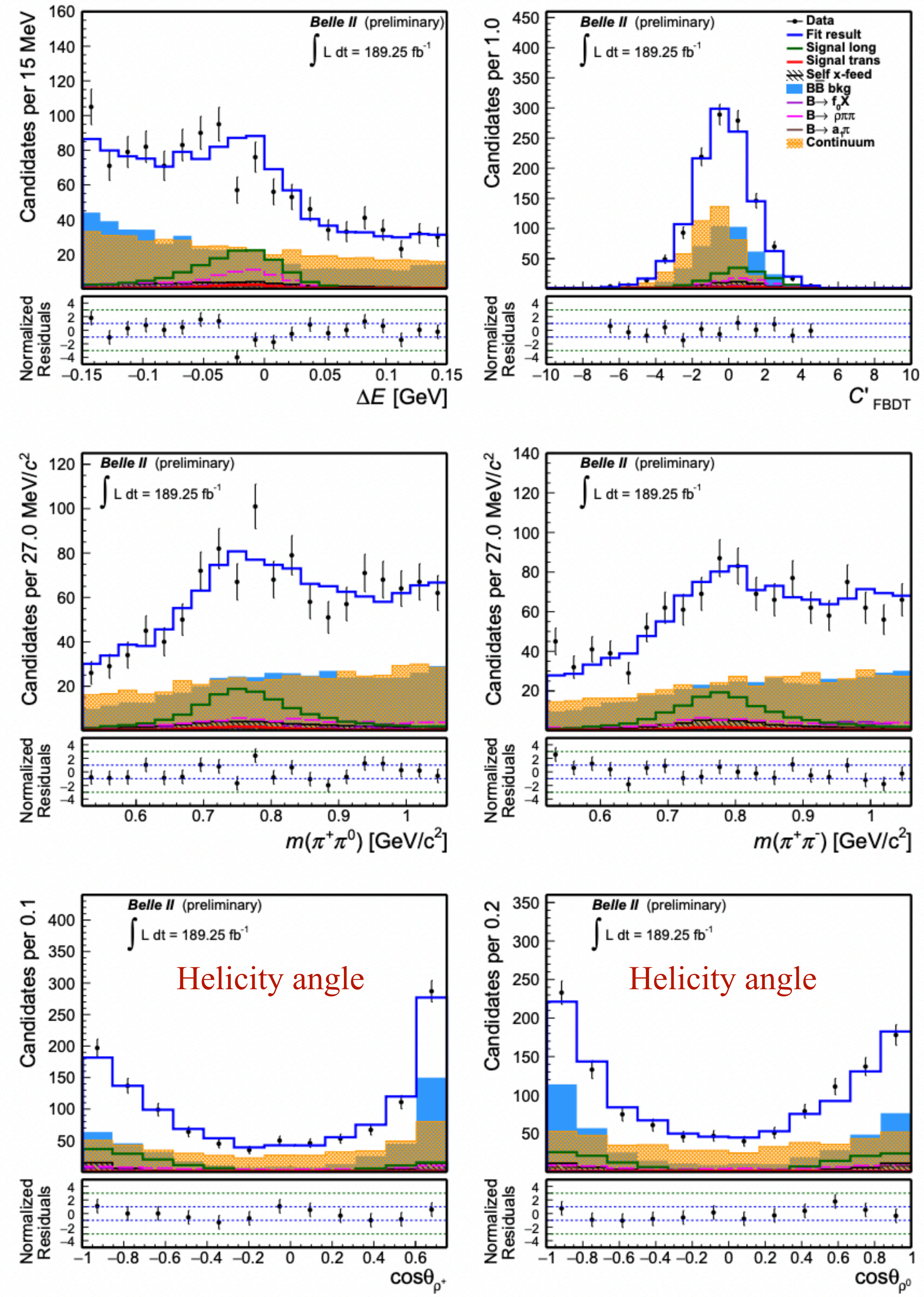
Analysis strategy

- 6D fit is performed to extract the yields
- Continuum and peaking background (with similar final state) complicates the analysis
- Validation: analysis procedure and continuum suppression inputs

Experiment	Values
Belle II (197 M BB pairs) **arXiv: 2206.12362**	$\mathscr{B} = (23.2\ {}^{+2.2}_{-2.1}\ \pm 2.7) \times 10^{-6}$ $f_L = 0.943\ {}^{0.035}_{-0.033}\ \pm 0.027$ $\mathscr{A}_{CP} = -0.069\ \pm 0.068\ \pm 0.060$
BaBar (465 M BB pairs) **PRL 102 141802 (2009)**	$\mathscr{B} = (23.7\ \pm 1.4\ \pm 1.4) \times 10^{-6}$ $f_L = 0.950\ \pm 0.015\ \pm 0.006$ $\mathscr{A}_{CP} = -0.054\ \pm 0.055\ \pm 0.010$

First uncertainty: stat.; second: syst.

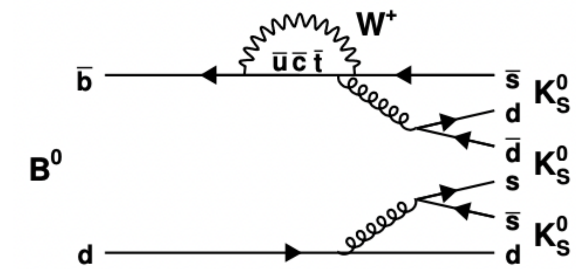
Consistent with previous measurements, however, dominated by systematic uncertainties



Time-dependent CPV measurement

3 body decays: Time dependent CPV analysis: $B^0 \to K_s^0 K_s^0 K_s^0$

- Target: $\mathscr{B}$ and CP aysymmetry
- Process mediates via $b \to sq\bar{q}$ transition
- It is sensitive to non-SM effects
- Important for understanding the CP asymmetry



$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}(1 + q[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)])$$

Mixing induced CPV — Direct CPV

Any significant deviation of $\mathscr{A}_{CP}$ and $\mathscr{S}_{CP}$ from prediction of SM may be a hint of NP !

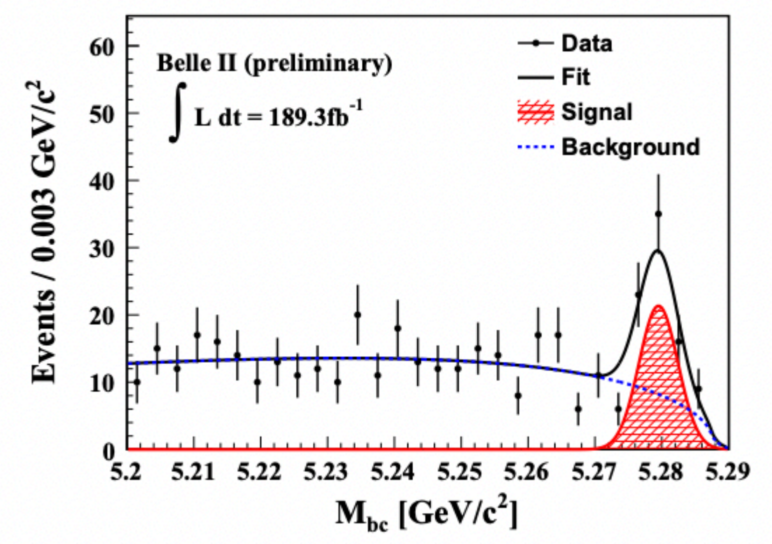
$\mathscr{S} = -\sin 2\phi_1$	**SM prediction**	$\mathscr{A} = 0$
$= -0.83 \pm 0.17$	**World average**	$= 0.15 \pm 0.12$

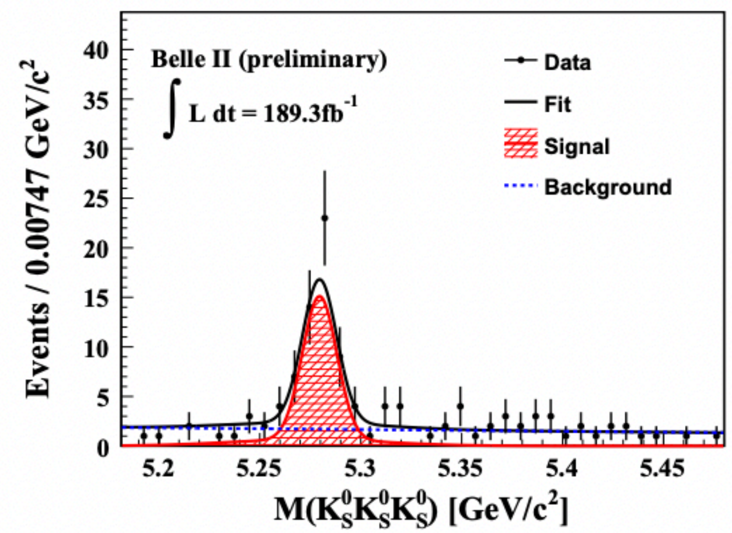
Analysis strategy

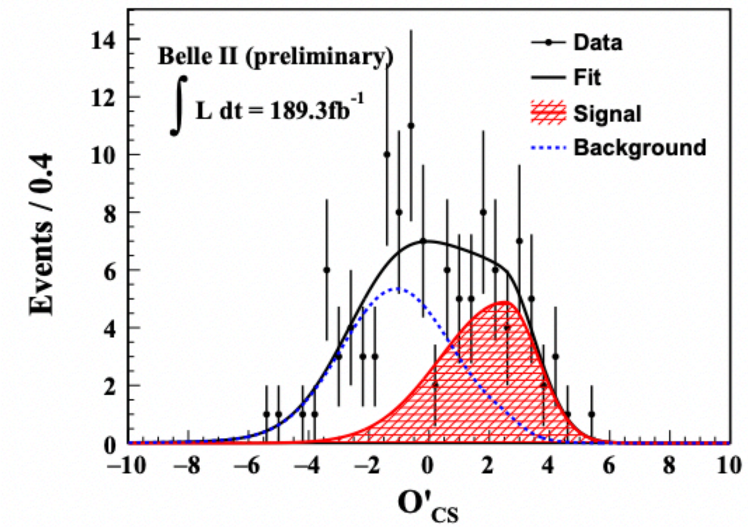
- Sigal extraction using a 3D fit function comprising of: M_{bc}, $M(K_s^0 K_s^0 K_s^0)$, $\mathscr{O}'_{CS}$
- Continuum events pose as dominant background: BDT classifiers for suppression
- Additional backgrounds from, $B^0 \to X(\to K_s^0 K_s^0) K_s^0$ due to $b \to c$ transitions
- Veto $b \to c$ transitions through invariant mass, $M(K_s^0 K_s^0)$ selection criterion
- For CPV studies, Belle II flavor tagger algorithm is used to identify B_{tag} flavor
- Challenge is to correctly reconstruct K_s^0 vertex

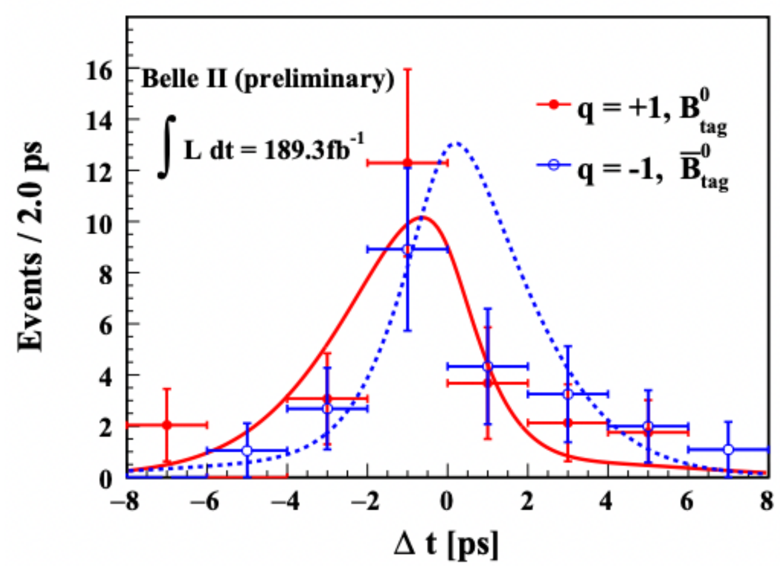
Time dependent CPV: $B^0 \to K_s^0 K_s^0 K_s^0$

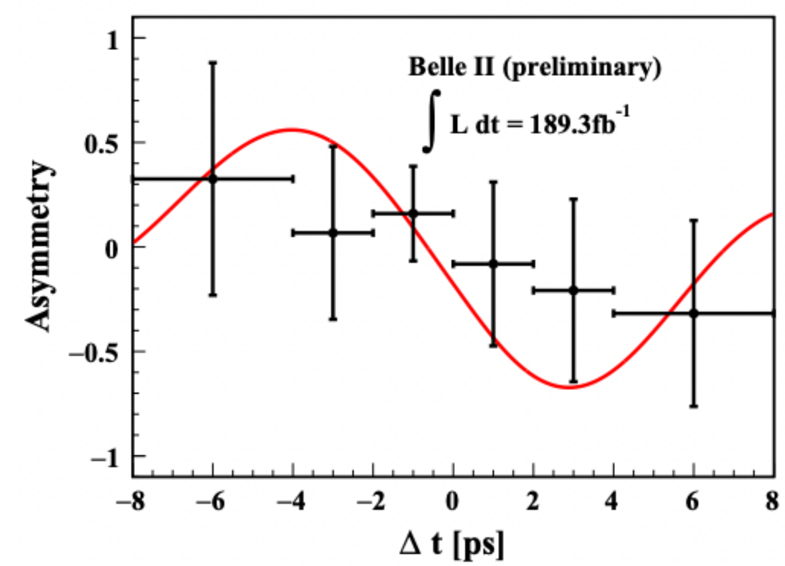
Signal yield = 53 ± 8











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$$\mathcal{S} = (-1.86\ ^{+0.91}_{-0.46}\ \pm 0.09$$

$$\mathcal{A} = -\,0.22\ ^{+0.30}_{-0.27} \pm 0.04$$

World Average value

$$\mathcal{S} = -\,0.83 \pm 0.17$$

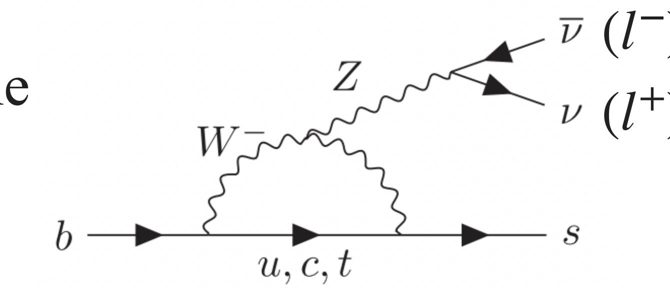
$$\mathcal{A} = 0.15 \pm 0.12$$

First uncertainty: stat.; second: syst.

Electroweak and radiative penguin decays

Electroweak and radiative 'penguins': $b \to s$

- A b quark decaying to an s/d quark requires the presence of a neutral vector boson at the vertex and a change of flavor (*Flavor changing neutral current*: FCNC)
- These, $b \to s$ FCNC processes are suppressed at 'tree' level within SM due to GIM
- However, can occur through loop-level within the SM
- New particles can couple to the SM particles an can influence its predictions, thereby making FCNC decays potent probe for NP searches



Theoretical Challenges

- Need to consider different kinematic regions to probe the complete q^2 spectrum
- Affected by form factor uncertainties

$q^2 = M(l\bar{l})$

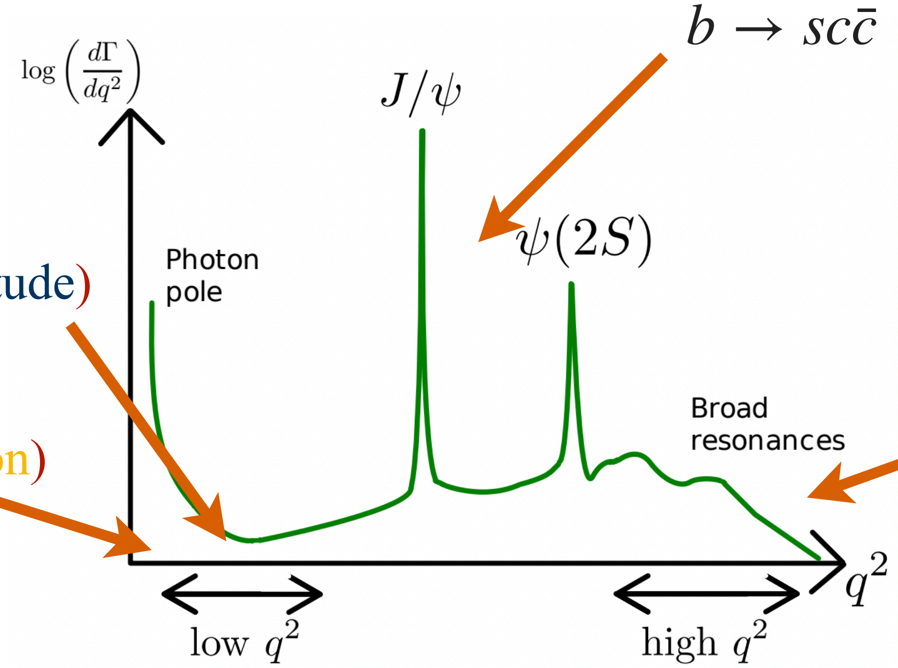
$b \to sl\bar{l}$

$b \to sc\bar{c}$ (background)

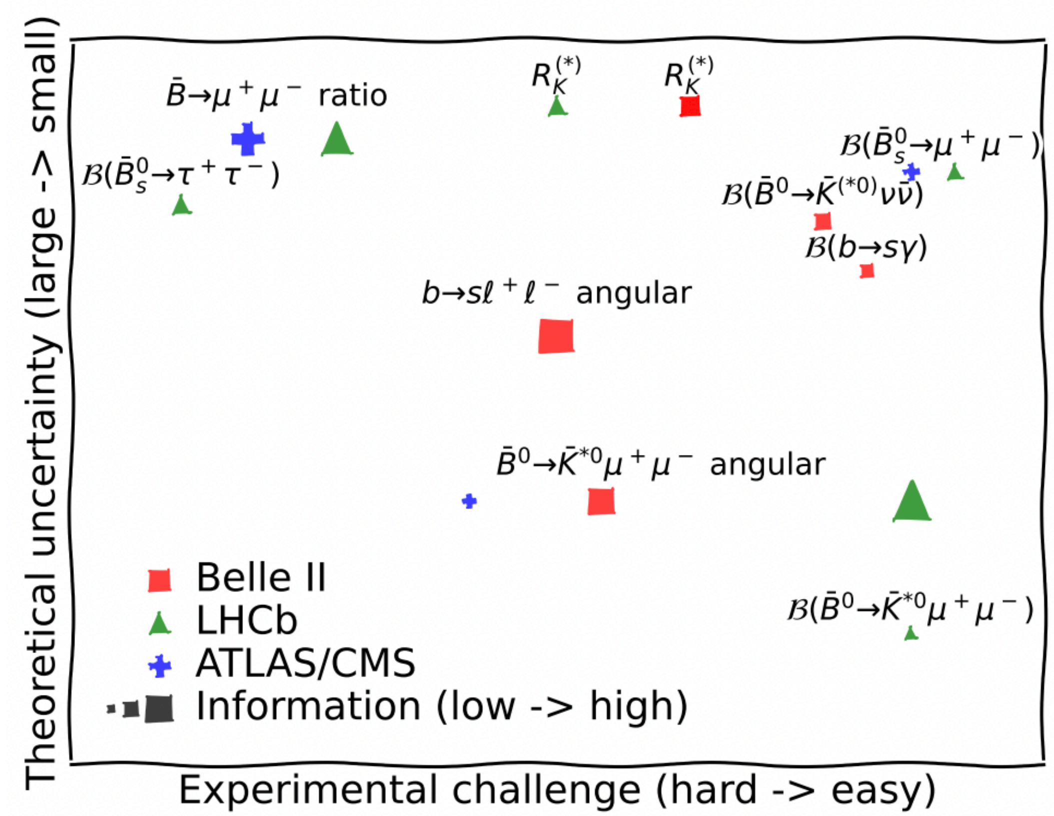
$b \to sl\bar{l}$ (penguin amplitude)

$b \to sl\bar{l}$ (virtual photon)

$b \to sl\bar{l}$ (interferences from Ψ)



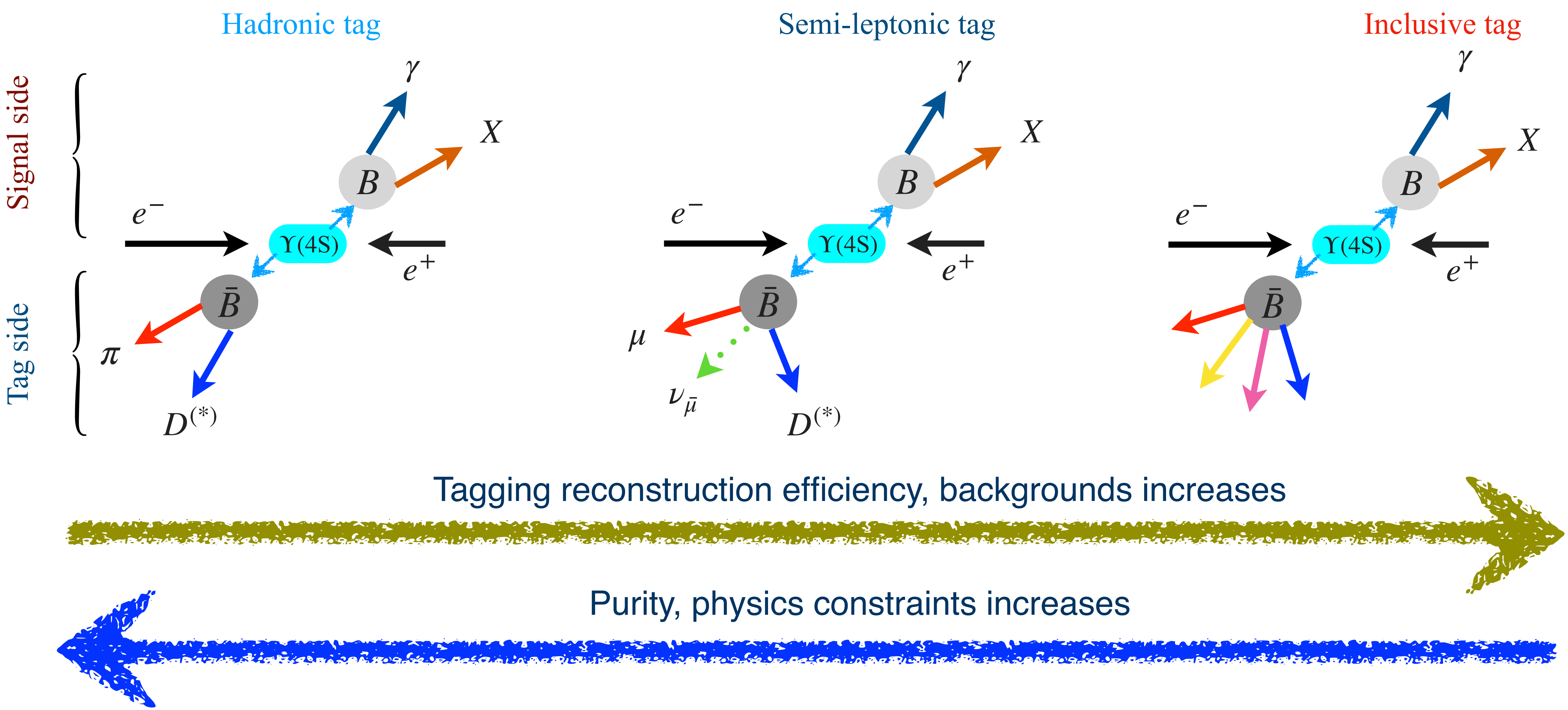
arXiv: 2205.05222v1



A single measurement is not sufficient!

Experimental challenges: missing particles / inclusive measurements

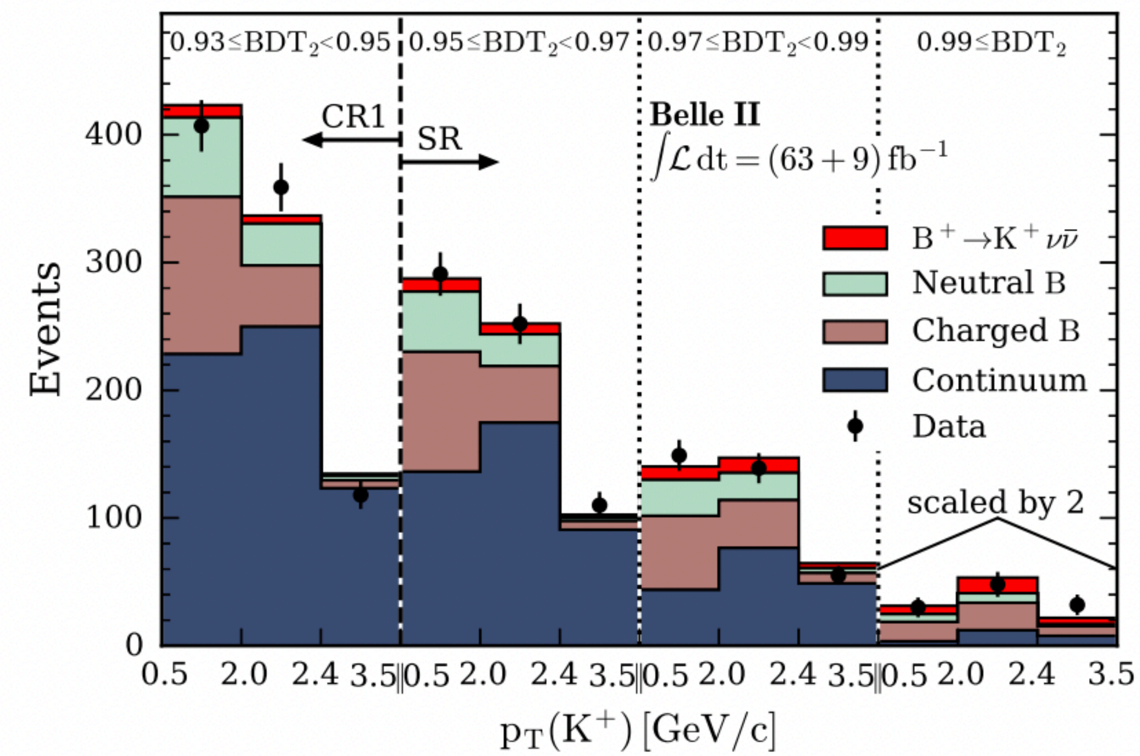
- Missing final state particles or inclusive measurements are experimentally very challenging
- e^+e^- colliders such as Belle II are best suited for such kind of measurements because of 4π coverage
- These measurements are performed using the principle of conservation of momentum and identifying the conjugate B-meson very precisely (the tagging approach)
- Three types of tagging: Exclusive (hadronic), Semi-exclusive (semi-leptonic), and inclusive tagging



Search for $B^+ \to K^+\nu\bar{\nu}$ using inclusive tagging method

PRL 127 181802 (2021)

- Vary challenging due to missing particles in the signal-side B meson
- ***An inclusive tag approach adopted for the first time at Belle II***



Analysis strategy

- Charged tracks and neutral clusters are identified with preliminary selection criteria to remove backgrounds
- Multivariate analysis techniques: 2 BDT classifiers used in cascade to separate signal from background, additional binary classifier to correct for mismodelling of qqbar events

Signal efficiency

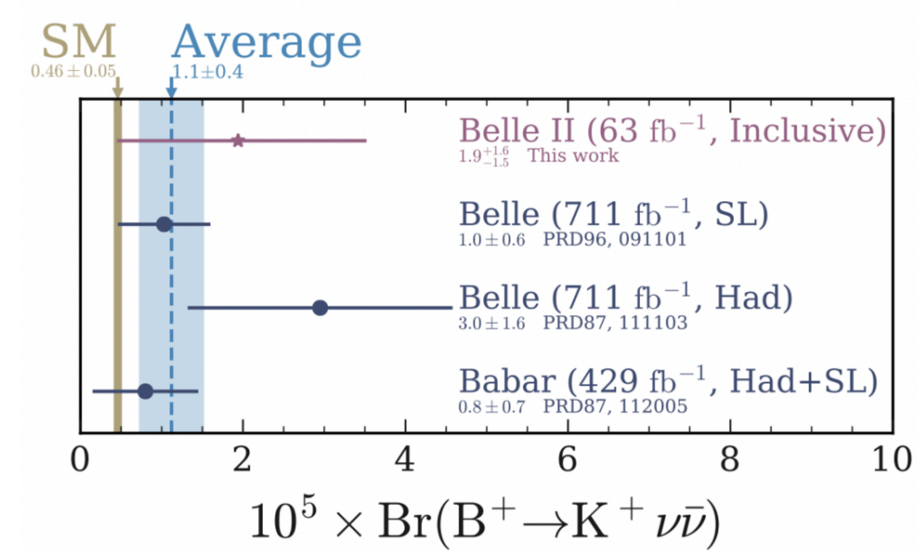
$$\epsilon^{incl} = 4\,\% \quad \text{(Belle II, 63 fb}^{-1}\text{)}$$
$$\epsilon^{sl} = 0.2\,\% \quad \text{(Belle, 711 fb}^{-1}\text{)}$$
$$\epsilon^{had} = 0.06\,\% \quad \text{(Belle, 711 fb}^{-1}\text{)}$$

Signal yield $= 4.2\,^{+3.4}_{-3.2}$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (1.9\,^{+1.3}_{-1.3}\,^{+0.8}_{-0.7}) \times 10^{-5}$$

First uncertainty: stat.; second: syst.

Ul on the $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})$ at 90% CL $< 2.3 \times 10^{-5}$

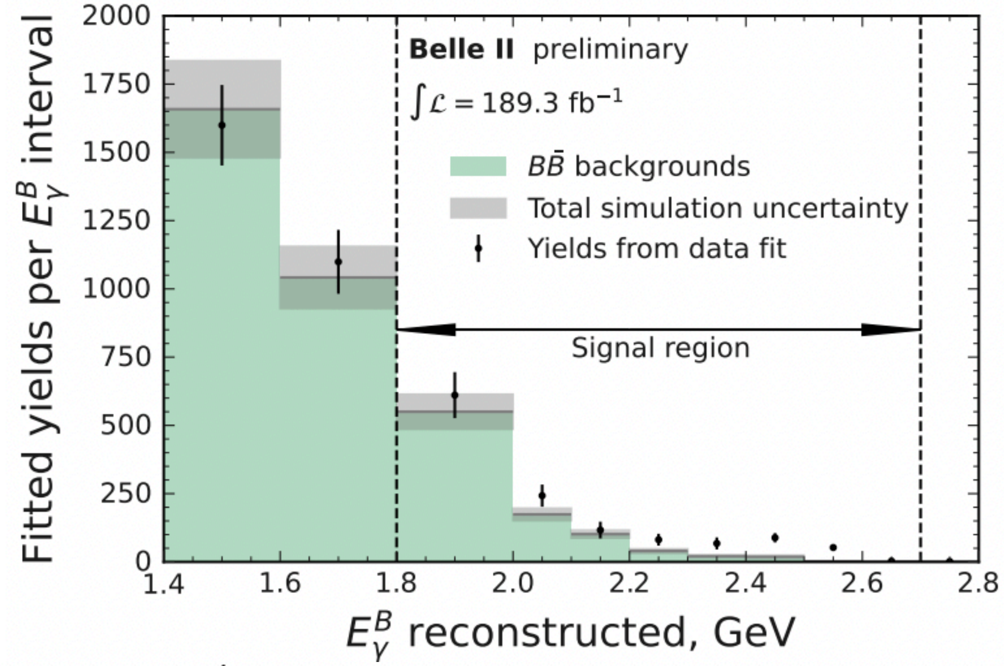


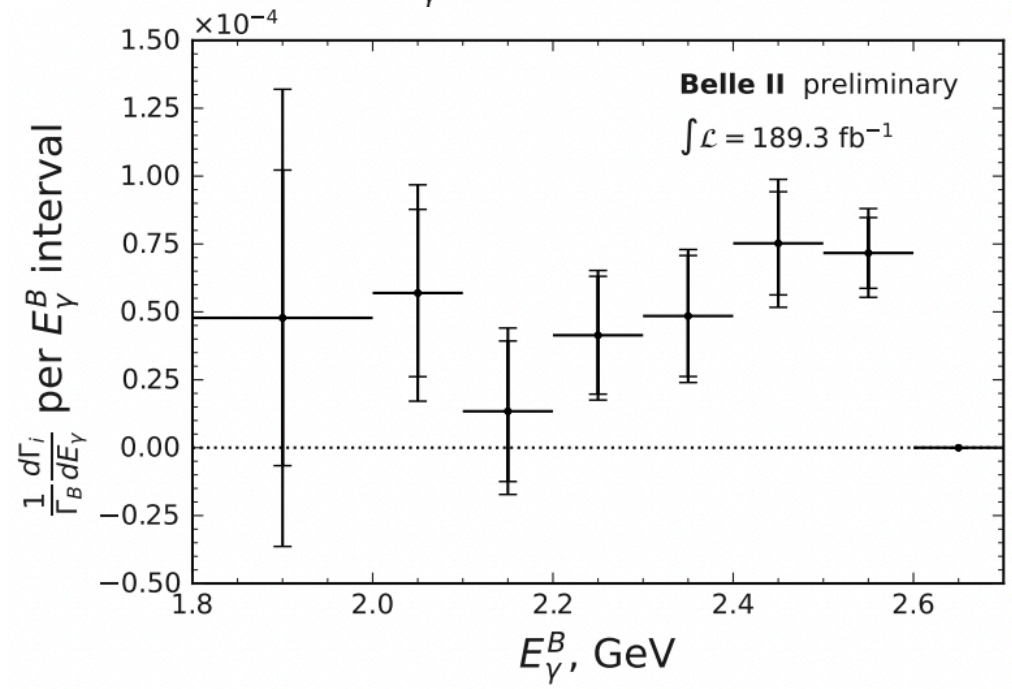
Radiative decay $B \to X_s\gamma$

- Target: Measurement of inclusive $\mathscr{B}$ for different E_γ^B threshold
- Experimentally challenging

Analysis strategy

- No kinematic selection criteria applied to select X_s
- The tag side is reconstructed using hadronic decay channels
- Signal region is identifed to be $1.8 < E_\gamma^B < 2.7$ (GeV)
- Fit strategy:
  1. Determine the well-reconstructed B_{tag} candidates using $M_{\rm bc}$ as a fit variable
  2. Background subtraction in E_γ^B distribution is carried out using MC simulation





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E_γ^B lower threshold	$\frac{1}{\Gamma_B}\frac{d\Gamma_i}{dE_\gamma}(10^{-4})$
1.8	3.55 ± 0.78(stat.) ± 0.84(syst.)
2.0	3.07 ± 0.56(stat.) ± 0.48(syst.)
2.1	2.50 ± 0.47 (stat.)± 0.35 (syst.)

PRD 77, 051103 (2008)

BaBar's hadronic tag result, $E_\gamma^B > 1.9$ (GeV) (210 fb^{-1})

$$(3.66 \pm 0.85 \pm 0.60) \times 10^{-4}$$

Competitive with BaBar's measurement !

Preparations to test Lepton Flavor Universality

Preparations to test LFU: $\mathscr{R}(X_{e/\mu}) = \mathscr{B}(B \to X_c e\nu)/\mathscr{B}(B \to X_c \mu\nu)$

- The SM predicts the coupling strength of the weak interaction to be uniform for all of the lepton families: LFU
- This prediction needs to be experimentally verified and complementary measurements are a necessity
- SM prediction, $\mathscr{B}(B \to X_c \tau\nu) = (2.45 \pm 0.10)\,\%$ and sum of exclusive decays, $\mathscr{B}(B \to D\tau\nu) + \mathscr{B}(B \to D^*\tau\nu) = (2.30 \pm 0.67)\,\%$ (dominated by large uncertainties)

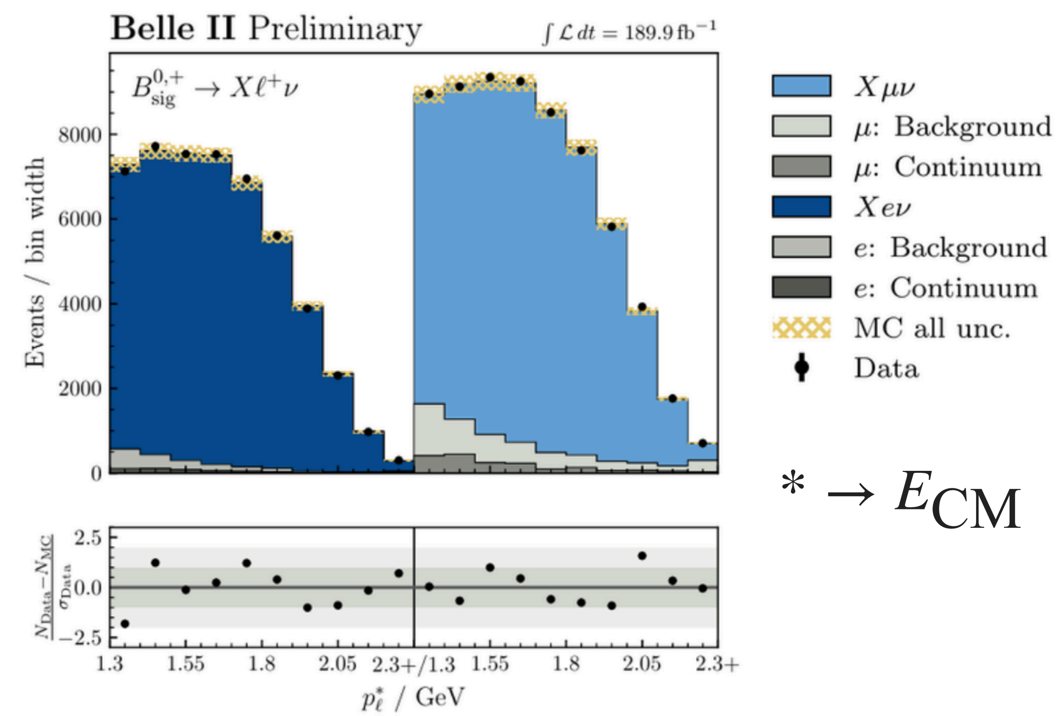
- Target: To measure light lepton ratio and validate the analysis strategy

Analysis strategy

- An event is identified as: $\Upsilon(4S) \to B_{tag} + (l^{\pm} + ROE)$
- B_{tag} candidates are reconstructed using FEI hadronic tagging algorithm
- Continuum and other B backgrounds affect the analysis
- Continuum is constrained with off-resonance data and B backgrounds are suppressed using background enriched control regions

ICHEP 2022	Most precise measurement!
$\mathscr{R}(X_{e/\mu})(p_l^* > 1.3 \text{ GeV})$	1.033 ± 0.010 (stat.) ± 0.020 (syst.)
Belle ($\mathscr{R}(D^*_{e/\mu})$) (exclusive)	1.01 ± 0.01 (stat.) ± 0.03 (syst.) PRD 100 052007 (2019)

Compatible with exclusive Belle measurement at 0.6σ



$* \to E_{\text{CM}}$

p_l^*/GeV

Next step: $\mathscr{R}(X) = \dfrac{\mathscr{B}(B \to X\tau\nu)}{\mathscr{B}(B \to Xl\nu)}$

Summary

✓Presented results corresponding to an integrated luminosity of 190 fb^{-1} on the following topics

* Charm lifetime measurements
* Tagged and untagged exclusive measurements on $|V_{cb}|$ and $|V_{ub}|$
* Measurements to verify the isospin sum rule
* α/ϕ_2 measurement
* Time dependent CP violation measurements on three body decays
* Electroweak and radiative peguin decays
* Preparations to test the lepton flavor universality

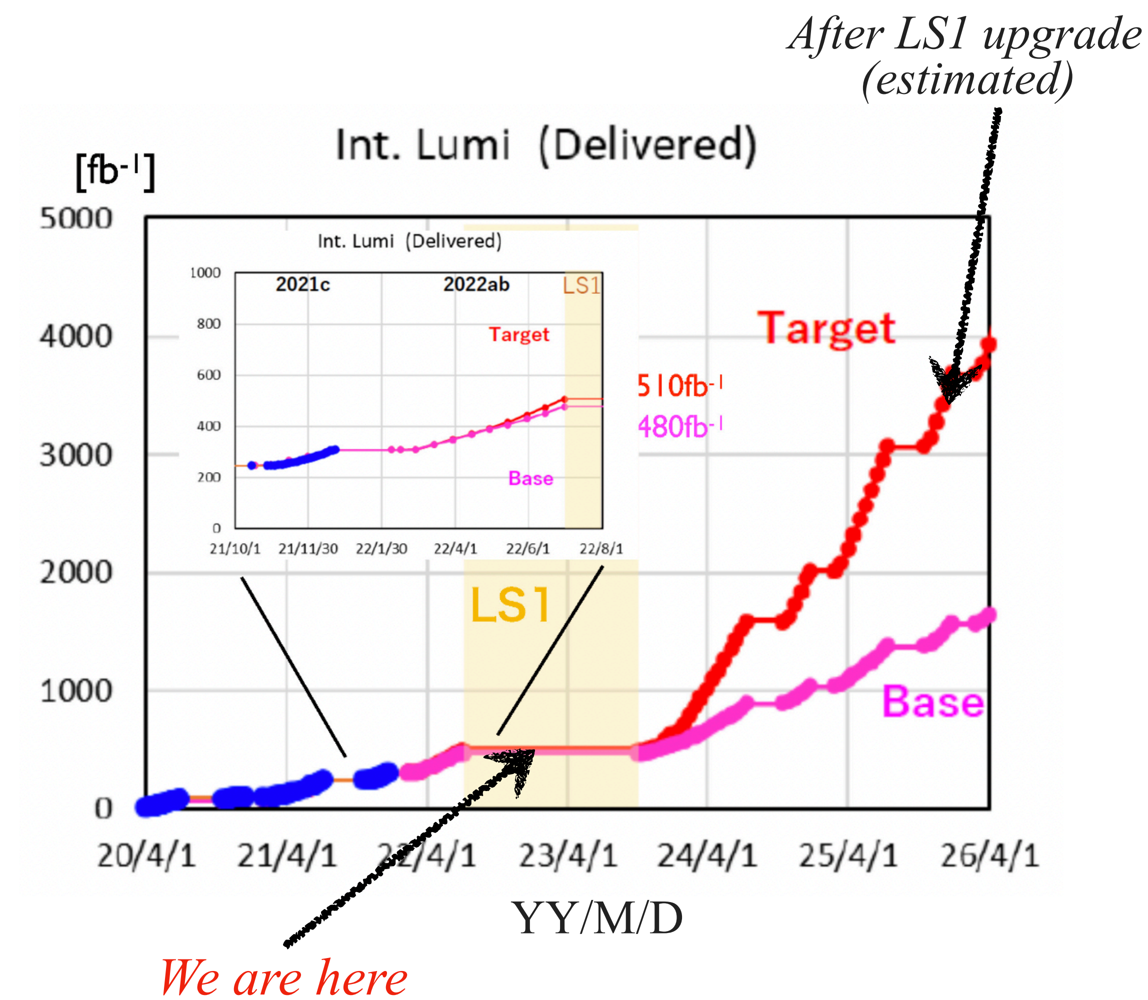
✓All these measurements agree well with the world average values and in some does better than the previous generation e^+e^- colliders (Babar/Belle) with limited statistics

❖Some interesting results from the dark sector, charmonium and τ physics could not be accomodated here, due to the broad physics program of Belle II

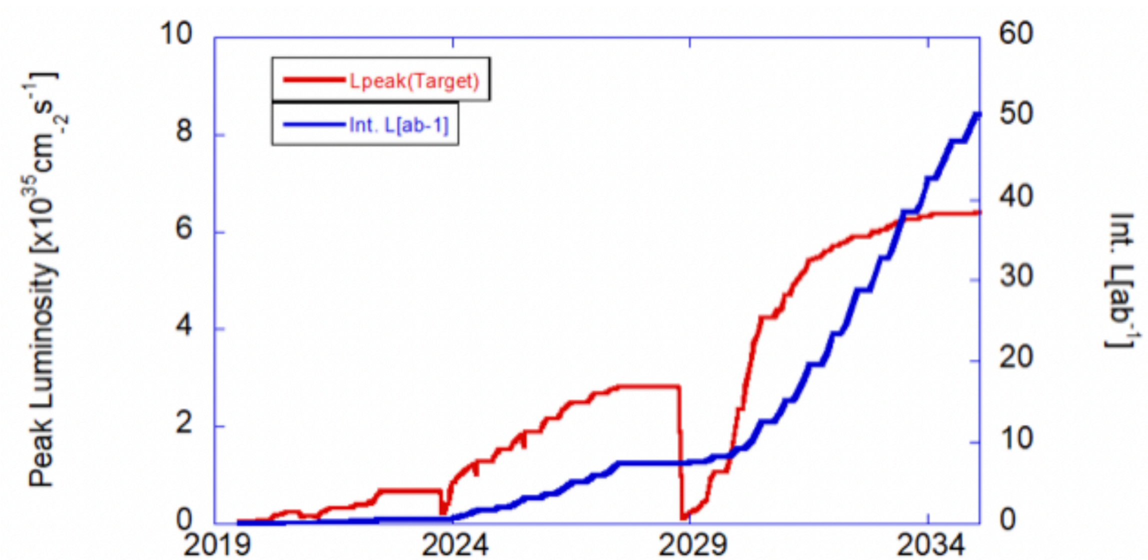
Future prospects

Observables	Exp. theor. accuracy	Exp. experim. uncertainty	50 ab^{-1}
UT angles and sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0 \pi^0)$ [10^{-2}]	***	4	Belle II
$\mathcal{A}(B \to K^+ \pi^-)$ [10^{-2}]	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau \nu)$ [10^{-6}]	**	3%	Belle II
$\mathcal{B}(B \to \mu \nu)$ [10^{-6}]	**	7%	Belle II
$R(B \to D \tau \nu)$	***	3%	Belle II
$R(B \to D^* \tau \nu)$	***	2%	Belle II/LHCb
Radiative and EW penguins			
$\mathcal{B}(B \to X_s \gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d} \gamma)$ [10^{-2}]	***	0.005	Belle II
$S(B \to K_S^0 \pi^0 \gamma)$	***	0.03	Belle II
$S(B \to \rho \gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma \gamma)$ [10^{-6}]	**	0.3	Belle II
$\mathcal{B}(B \to K^* \nu \bar{\nu})$ [10^{-6}]	***	15%	Belle II
$R(B \to K^* \ell \ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu \nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau \nu)$	***	2%	Belle II
$A_{CP}(D^0 \to K_S^0 \pi^0)$ [10^{-2}]	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0 \pi^+ \pi^-)$	***	0.03	Belle II
$A_{CP}(D^+ \to \pi^+ \pi^0)$ [10^{-2}]	**	0.17	Belle II
Tau			
$\tau \to \mu \gamma$ [10^{-10}]	***	< 50	Belle II
$\tau \to e \gamma$ [10^{-10}]	***	< 100	Belle II
$\tau \to \mu \mu \mu$ [10^{-10}]	***	< 3	Belle II/LHCb

Belle II holds promise in giving us new insights through precision measurements



Long term projection



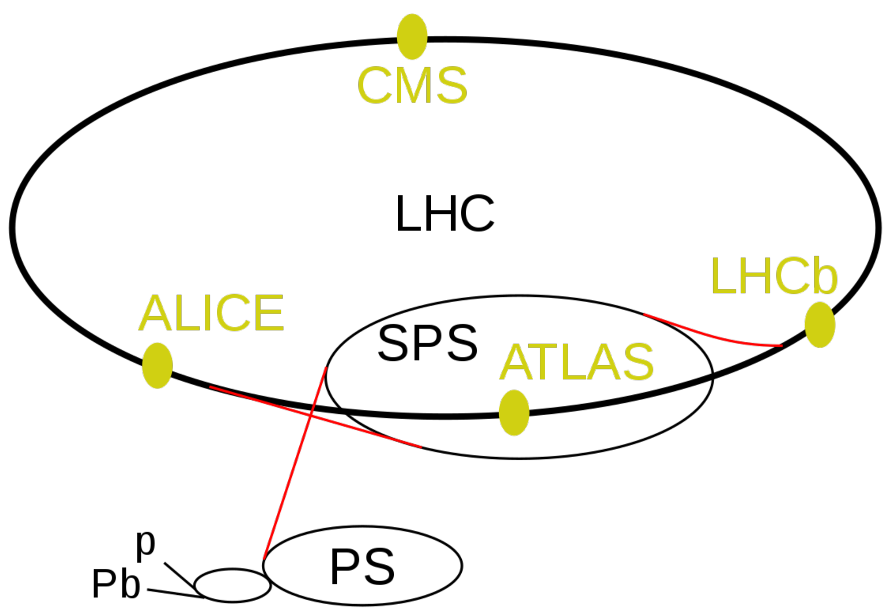
Thank You

Additional slides

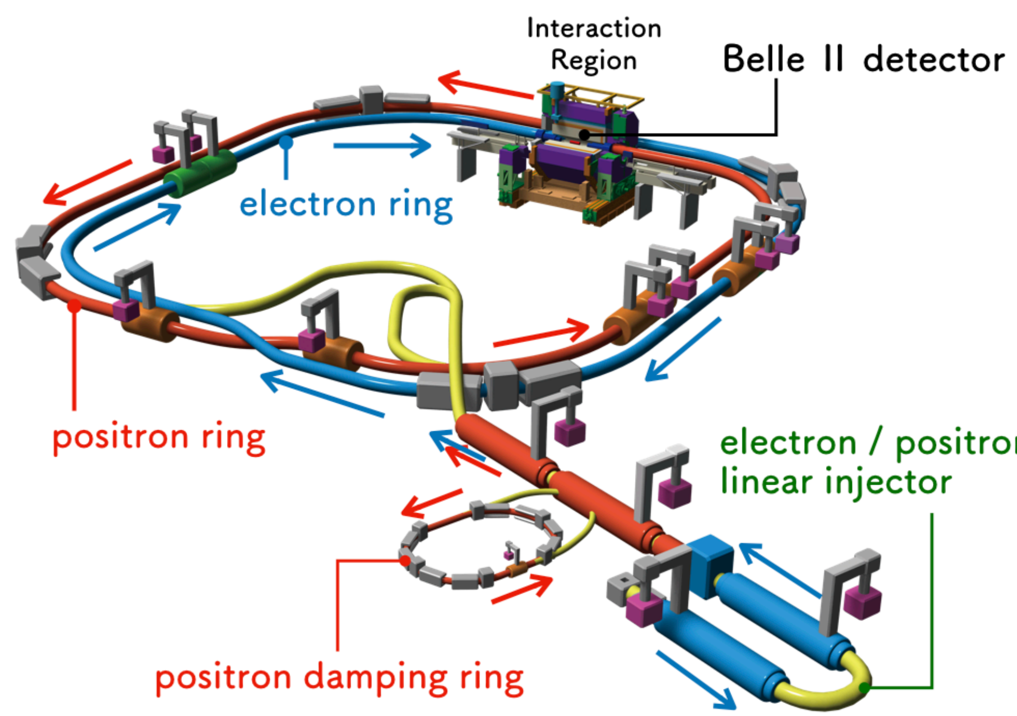
Types of colliders

- At present (on earth), colliders are the only way to create an environment similar to our early universe

Hadron Collider



Electron-Positron Collider



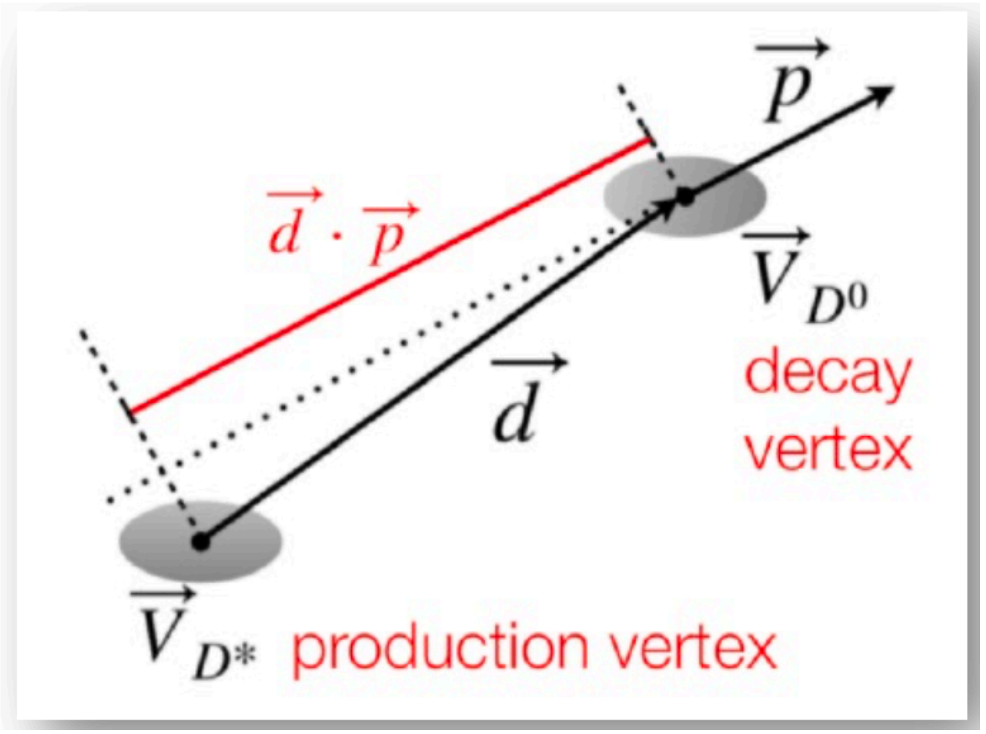
(Belle II)

- Energy frontier (13.6 TeV, $\sim 2.06 \times 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- Capability to produce almost all SM particles
- Huge amount of backgrounds from *pp* collisions ($\sim$ 20 inelastic events per crossing (30M crossing/sec))

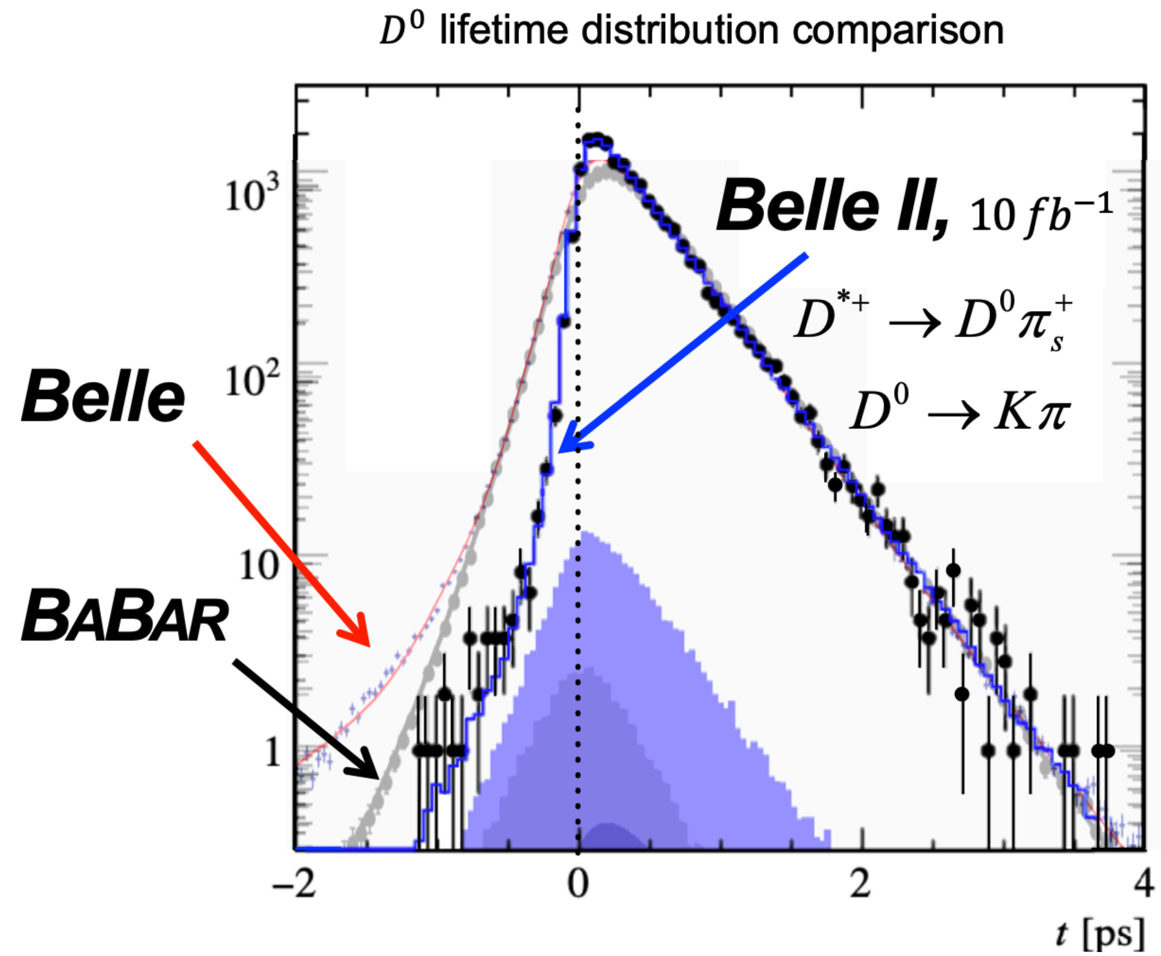
- Luminosity frontier (Design $\mathscr{L} = 6 \times 10^{35}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- Threshold production of particles
- Compared to *pp* collisions, e^+e^- collisions produce fewer backgrounds: a clean environment

Both frontiers are necessary for understanding the Nature !

Lifetime measurements of $D^+, D^0, \Lambda_c^+, \Omega_c^0$



$$t_h = \frac{m_h}{p^2} \vec{d} \cdot \vec{p}$$



Improvement of Belle 2 over Belle

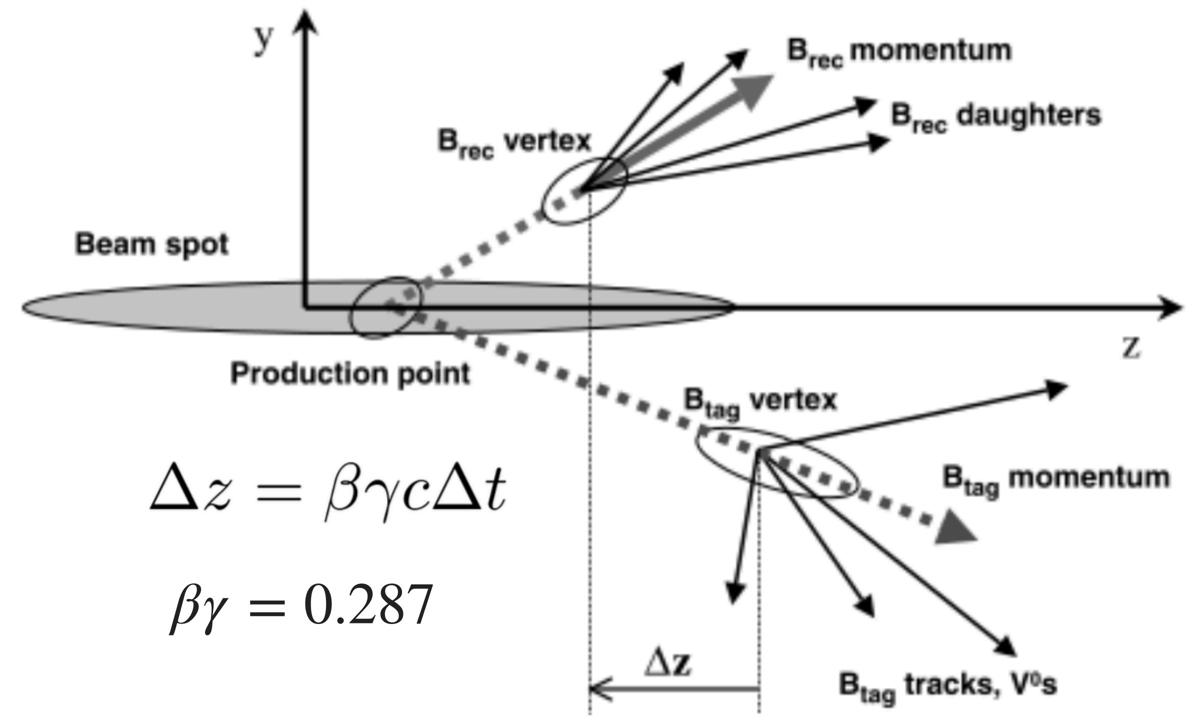
- 2 times better vertex resolution
- 20 times smaller beam spot size

Behind the scenes: Time dependent CPV decays

$$\mathcal{A}_{\text{CP}}^{B\to f}(\Delta t) \equiv \mathcal{S}\,\sin(\Delta m_d \Delta t) + \mathcal{A}\,\cos(\Delta m_d \Delta t)$$ Sensitive to Δt

Determination of Δt :

- Requires the measurement of Δz.
- Δz measurement requires the correct reconstruction of B_{tag} and B_{rec} vertices.
- Vertex reconstruction can be done only from tracks.
- First, B_{rec} is fully reconstructed and the remaining tracks are assigned to rest-of-event (ROE) category.
- ROE events are subjected to selection criteria (min. hits in vtx. detector, IP constraints etc.)
- Subsequently, all tracks from ROE are combined to form the B_{tag} vertex (on the basis of some FOM, X^2)



$$\Delta z = \beta\gamma c \Delta t$$

$$\beta\gamma = 0.287$$

Factors affecting Δt resolution :

- B_{tag} , B_{rec} vertex resolution
- Resolution of the boost factor, βγ determined from the beam energy

- For a typical $\Delta z \sim 100\ \mu m$
- Δt resolution is 0.6 ps $< \tau_B(1.5\text{ps})$
- Δt resolution is 0.6 ps $< \tau_{B\to\bar{B}}(12.5\text{ps})$

B_{tag} is B or $\bar{B}$? → ***Flavor tagging***

Charmless B decays : Isospin sum rule

- Target : Measurement of $\mathcal{B}$ and direct $\mathcal{A}_{CP}$
- Process mediates via $b \to sq\bar{q}$ 'loop' diagrams.
- To address the $K\pi$ puzzle, precise measurement of $\mathcal{B}$ and $\mathcal{A}_{CP}$ is important.

$B^0 \to K^+\pi^-$, $B^+ \to K^0\pi^+$ — 62.8 fb^{-1}

New: $B^+ \to K^+\pi^0$, $B^0 \to K^0\pi^0$ — 190 fb^{-1}

2D **signal extraction function**

- $M_{bc} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$
- $\Delta E = \mathrm{E}^*_B - E^*_{beam}$
- M_{bc} and ΔE correlations are taken into account

Backgrounds analyzed

- $e^+e^- \to q\bar{q}$ (q = u, d, s, c)
- $b \to c$ mediated decays
- $b \to u,\ d,\ s$ mediated decays
- Multivariate analysis is employed to suppress continuum

Charged track identification

- Tracks momentum information from dE/dx in CDC
- Particle identification using Cherenkov detectors
- pion/Kaon misidentification is 9%/11%

Neutral pion reconstruction

- Reconstructed from γ's deposited in ECL
- ECL selection criteria (forward/barrel/backward)

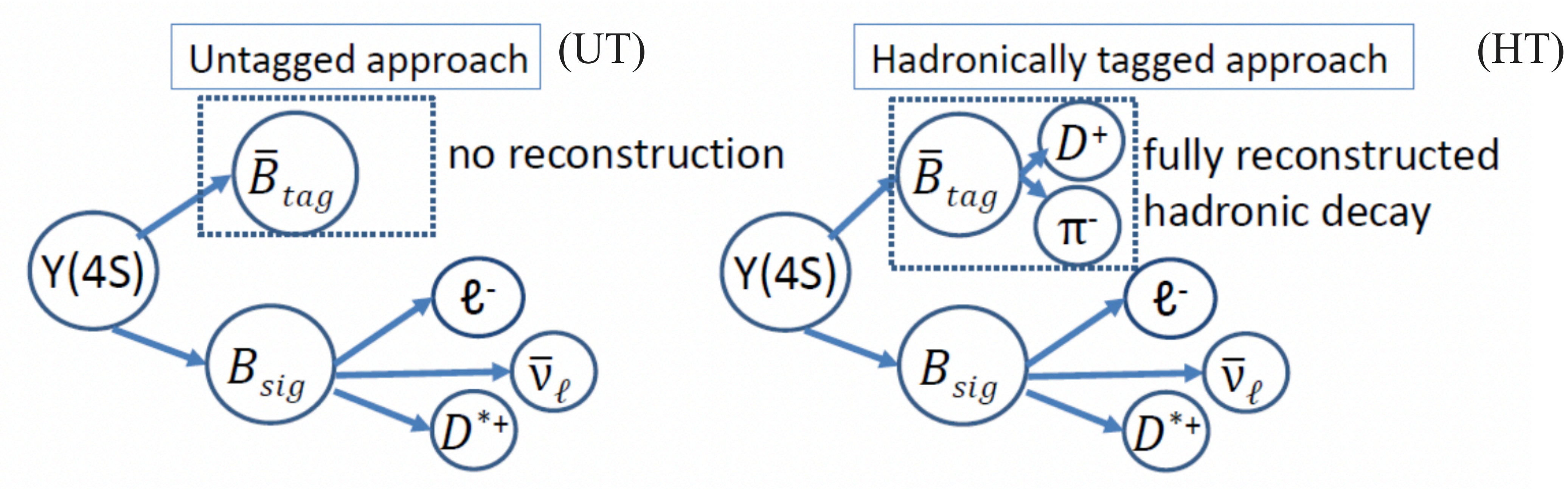
K^0_s reconstruction (challenges)

- Dipion invariant mass 'cuts'
- K^0_s flight distance
- Angle between dipon momentum and K^0_s flight direction

Analyses mostly affected by continuum backgrounds

$|V_{cb}|$ and $|V_{ub}|$ measurements strategy

- $|V_{cb}|, |V_{ub}|$ measurements are experimentally very challenging owing to missing particles in the final state
- Both untagged and tagged approaches are adopted to complement each other.
- Untagged approach provides higher efficiency in signal reconstruction with a trade-off in signal purity
- Whereas tagged approach has lower signal efficiency but has higher purity



Advantages at Belle II

- Threshold production of $B\bar{B}$ pairs
- e^+e^- provides a 'clean' environment for reconstruction
- Missing momentum of undetected particles can be calculated due to 4π detection of other particles in an event